Exploiting Thermal Effects for Self-Adaptive Resonator Stabilization and Polarization Mode Engineering in High-Power Lasers

Inauguraldissertation
der philosophisch-naturwissenschaftlichen Fakultät
der Universität Bern

vorgelegt von
Michelle S. Roth
von Fahrni

Leiter der Arbeit:
Dr. V. Romano
Institut für Angewandte Physik, Universität Bern

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Von der Philosophisch-naturwissenschaftlichen Fakultät angenommen.

Bern, 22.12.2005

Der Dekan
Prof. Dr. P. Messerli

I am among those who think that science has great beauty.
A scientist in his laboratory is not only a technician:
he is also a child placed before natural phenomena
which impress him like a fairy tale.

Marie Curie (1867 - 1934)

Contents

Introduction

It was in 1917 when A. Einstein published his quantum theory of radiation proposing a process called “stimulated emission”. Einsteins work laid the theoretical fundament for the laser, but his theories were presented only as hypotheses, because at that time Einstein did not describe a device that could achieve stimulated emission. It took several more decades before the first laser light source was actually built. Finally, in 1960 T. Maiman published his results on stimulated optical radiation in ruby. This first laser, consisting of a flashlamp-pumped ruby crystal, was only capable of pulsed operation. A few months later A. Javal demonstrated the first gas laser based on helium and neon. In 1962 the laser diode was invented and two years later the first Nd:YAG and CO_2 lasers were presented. In the following years numerous materials were found that posses a suitable set of energy levels to support laser action.

Although the laser was a breakthrough from the technical point of view, it was called a “solution looking for a problem” in the first years after its invention. But only a decade later lasers had expanded into many fields of science and technology. The broad spectrum of different wavelengths from X-rays to infrared and the wide range of powers, that are provided by the various types of lasers offer numerous applications, e.g. in data communication, scientific research, medicine and industry. In the field of material processing, such as cutting and welding, CO_2 and Nd:YAG lasers became very common. In high-power applications CO_2 lasers were the first choice for many years, but with the development of reliable and affordable laser diodes they are slowly replaced by diode-pumped solid-state lasers.

Some of the advantages of solid-state lasers are, that they are generally smaller, more compact, simpler in design, and that they emit wavelengths in the near infrared region, which are very suitable for metal processing. However, especially at high power levels, thermal problems occur in solid-state lasers. High pumping powers generate a huge amount of heat in the laser crystal, which must be dissipated by external cooling. This causes a temperature gradient in the laser medium, which leads to a number of disadvantageous thermal effects. The results are beam distortions due to a thermally induced lens, depolarization losses because of stress induced birefringence, or even fractures of the laser rod if the thermally induced stress exceeds the tensile strength of the laser material. All these effects severely affect the output power and the beam quality of the laser. Their influence on the laser performance depends on various factors, such as thermo-optical and mechanical material properties, the geometry of the laser crystal, pumping and cooling geometries, or the resonator design. Hence, numerous approaches to eliminate unfavorable thermal effects in solid-state lasers have been published.

This work concentrates on the compensation of the thermally induced lens by a

method that exploits the thermal lens itself. The main contribution to the thermal lens in a pumped laser crystal comes from the fact that the refractive index of a material changes with temperature. In most crystalline solid-state laser materials the refractive index grows with increasing temperature. Simultaneous pumping and edge-cooling of a laser rod leads to a radial temperature distribution and, thus, to a focusing gradient index lens. In other materials, such as glasses or liquids, the temperature dependance of the refractive index, the so-called thermal dispersion, exhibits a negative sign and the same radial temperature gradient as above will generate a negative or defocusing lens. This offers the possibility to design temperature-driven adaptive optical components, which can be used to compensate for thermally induced optical aberrations in laser crystals. Often, liquids possess a rather strong thermal dispersion and are ideally suited to serve as compensating lenses, as already thin layers and/or small amounts of absorbed power produce a thermal lens of the desired strength.

The first two parts of this thesis are concerned with the compensation of the thermal lens in end-pumped Nd:YAG lasers. At low powers, end-pumped resonator configurations are often preferred to side-pumped systems as they allow for higher efficiencies and make it easier to achieve fundamental mode operation. But at higher powers, severe thermal problems arise. Due to the inhomogeneous temperature distribution in the laser medium the thermal effects are much stronger in end-pumped lasers than in transversally pumped lasers with the same pump power. The compensation of the thermal lens was achieved by sandwiching a thin liquid layer between the pumped face of the laser rod and a glass rod that serves as the resonator's HR end-mirror. The liquid then is heated through thermal contact with the laser rod, and a negative thermal lens is generated in the liquid which compensates for the positive thermal lens of the laser crystal. With this compensation the overall thermal lens could be reduced by almost an order of magnitude leading to a enormous extension of the resonator's stability regime.

Parts three and four present a compensation scheme for transversally pumped lasers. The so-called thermo-optically self-compensating amplifier (TOSCA), consists of two laser rods with a small layer of a gel sandwiched in between. Again, the gel layer adopts the temperature profile of the laser rods and compensates self-adaptively for the thermal lens. Experiments have shown that the self-compensating amplifier not only works for continuous wave but also for pulsed laser operation. Furthermore, the scheme also allows for a scaling to higher output powers by inserting multiple heads.

Part five describes how the thermal effects can be exploited to control the polarization mode of a laser. Tangentially or radially polarized laser beams become more and more important in many fields, such as material processing, trapping of metallic particles, vacuum acceleration of electrons, or focusing through high-numerical-aperture lenses. Due to the thermally induced birefringence in a laser rod, the focal length of the

thermal lens is different for radially and tangentially polarized light. Implementing an intracavity compensating element which comprises a thin layer of a liquid or gel, allows to discriminate the two polarization states and to produce an almost purely radially polarized laser beam. In addition the compensation of the thermal lens leads to an enhanced beam quality and a nearly unlimited range of stable laser oscillation.

Part 1

Self-adaptive compensation of thermal lenses in an end-pumped Nd:YAG laser

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Self-adaptive compensation of thermal lenses in an end-pumped Nd:YAG laser

M. S. Roth*, T. Graf and H. P. Weber

University of Bern, Institute of Applied Physics, Sidlerstrasse 5, CH-3012 Bern, Switzerland

ABSTRACT

In order to compensate for thermally induced lenses we have recently proposed and successfully demonstrated a new self-adaptive compensation scheme for transversally pumped laser rods. Now we show how this scheme can be simplified and adapted for end-pumped laser rods. The method is demonstrated with an end-pumped Nd:YAG laser and preliminary experimental results are presented.

Keywords: thermal lens, adaptive optics, laser resonators

1. INTRODUCTION

Recently we have successfully demonstrated the compensation of thermally induced lenses in transversally pumped laser rods by means of a self-adaptive compensating element (CE) placed inside the laser resonator. In a first approach we have proposed to use a rod of a suitable material (e.g. phosphate glass) that absorbs a small fraction of the intracavity laser radiation to generate a power-dependent compensating lens.[1] This negative thermal lens that is generated in the CE adaptively compensates for the varying positive lens in the laser rod (such as a transversally pumped Nd:YAG rod). In practice it was found that it is difficult to find or to develop a material that meets all the required properties (such as thermal dispersion, absorption, heat conductivity etc.) for an optimized thermo-optical compensation. As a consequence we developed a composite compensation scheme which comprises a thin liquid layer to generate the compensating lens.[2] The advantage of liquids is that they generally have a very strong thermal dispersion, which makes that only a thin layer and small heating powers are required to generate the desired lenses. In order to generate a power-dependent thermal lens in the CE a radial heat removal is required. This was achieved by filling the compensating liquid in a gap between two glass rods placed in a cooling mount. With this the heat generated in the CE due to the absorption of the intra-cavity laser radiation is removed mainly in radial direction which induces the desired power-dependent temperature profile.

In the original compensation scheme summarized above, the CE is arranged inside the resonator and the compensating lens has to be superimposed with the lens in the laser rod by means of relay optics as shown in Fig. 1, a). This set-up can be simplified by placing the compensating liquid layer directly at the location where it is needed. For transversally pumped lasers, the compensating layer is sandwiched in the middle between two laser rods as indicated in Fig. 1, b).[3] With this the temperature distribution in the laser rod is transferred to the compensating medium directly by the close heat contact. This compensation scheme can also be adapted for end-pumped lasers. In this case, the compensating liquid layer is placed between the pumped face of the laser rod and a glass rod that serves as the HR end-mirror as shown in Fig. 1, c). Again, the temperature distribution generated in the laser rod is transferred to the compensating layer by heat contact, leading to an optimum compensation of the thermally induced lens with varying laser power.

*Correspondence: EMail: michelle.roth@iap.unibe.ch, WWW: www.iap.unibe.ch

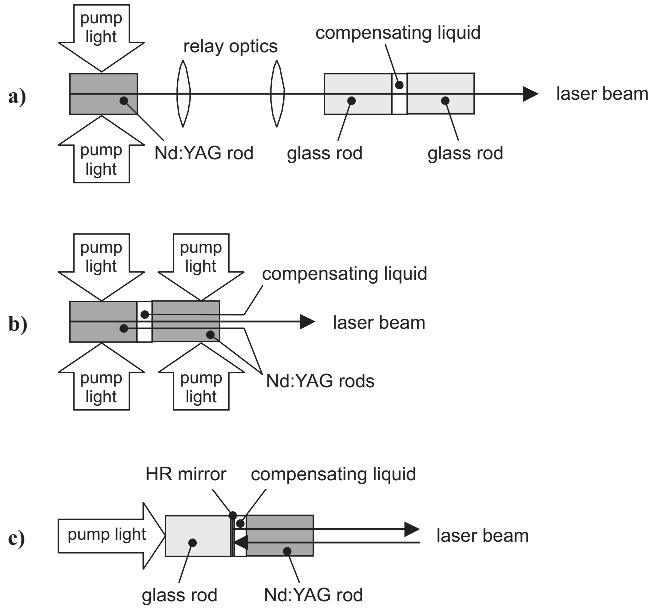

Figure 1. Compensation schemes. a) Transversally pumped laser with separate CE and relay optics. b) Transversally pumped laser with compensating liquid sandwiched between two laser rods. c) End-pumped pumped laser with compensating liquid sandwiched between laser rod and end mirror on a glass rod.

2. THERMAL EFFECTS IN END-PUMPED LASERS

In an end-pumped laser, the thermal lens is usually much stronger than in a transversally pumped laser with the same pump power. In a side-pumped laser the pump power is distributed more or less homogeneously along the rod which leads to a parabolic temperature profile. In an end-pumped laser the pump beam is usually smaller than the radius of the rod and the pump power is concentrated in the central region along the rod axis. This leads to a temperature profile that is parabolic in the central region and decays logarithmically towards the edges of the rod. If we assume a flat-topped pump profile in the pumped region, the temperature distribution can be described by the equation[4]

$$T(r) = T_0 + \frac{P_{abs}}{4\pi\kappa L} \cdot \begin{cases} -2ln\left(\frac{r_{pump}}{r_{rod}}\right) + 1 - \left(\frac{r}{r_{pump}}\right)^2, & r \leq r_{pump} \\ -2ln\left(\frac{r}{r_{rod}}\right), & r > r_{pump} \end{cases} \tag{1}$$

where T_0 is the temperature at the edge of the rod, P_{abs} the absorbed power, κ the heat conductivity and L the length of the rod. The radius of the laser rod is r_{rod} and the radius of the pump beam is r_{pump}.

Furthermore according to Beer's law the temperature is higher at the pumped end of the rod and decreases logarithmically towards the other end due to the absorption of the pump power.

To examine the thermal behavior of the compensated laser rod, finite element simulations were carried out. * The divergence of the pump beam was neglected as well as the absorption of pump power in the glass rod and the compensating liquid which is very small compared to the absorption in the Nd:YAG rod. The calculations fulfill the expectations for they show that the main part of the heat is deposited

*The program used for the finite element calculations was SESES, distributed by NM, numerical modelling GmbH, CH-8800 Thalwil.

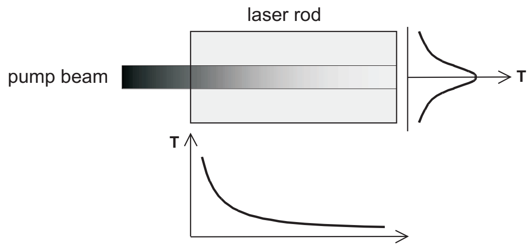

Figure 2. Schematic illustration of the temperature distribution in an end-pumped laser rod.

in the end of the Nd:YAG rod where the pump beam is focussed at and the temperature distribution in the liquid is generated by heat conduction. Fig. 3 shows a cut along the axis through the rods.

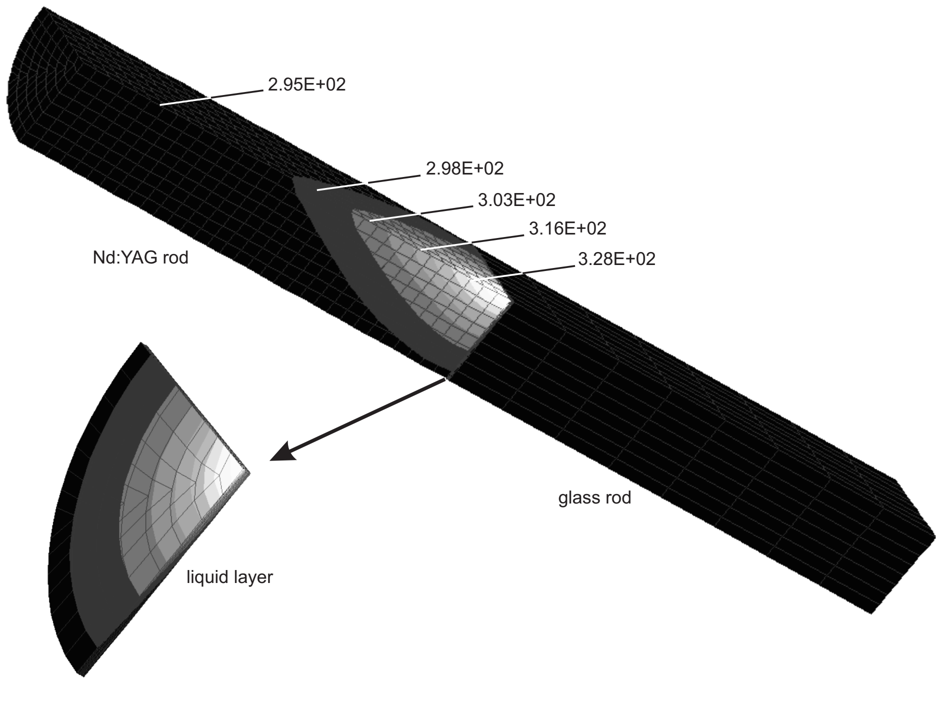

Figure 3. Finite element simulation of the heat distribution in the Nd:YAG rod, the glass rod and the compensating liquid in between. The thickness of the liquid layer is 0.1 mm and the pumping power 12.5 W. (Temperatures in Kelvin degrees)

The temperature profile along the longitudinal axis in the center of the rod was calculated for different values of the pump power (see Fig. 4). As discussed above (see also Fig. 2) the temperature in the laser rod decays logarithmically due to the absorption.

Fig. 5 shows the temperature profiles of the compensating liquid at the surfaces of the transition from the liquid to the Nd:YAG rod (graph a)) and from the liquid to the glass rod (graph b)). The thickness of the layer is 0.1 mm. Both profiles are in horizontal direction through the center of the surfaces. The significant temperature difference between these two profiles is due to the small value of the heat

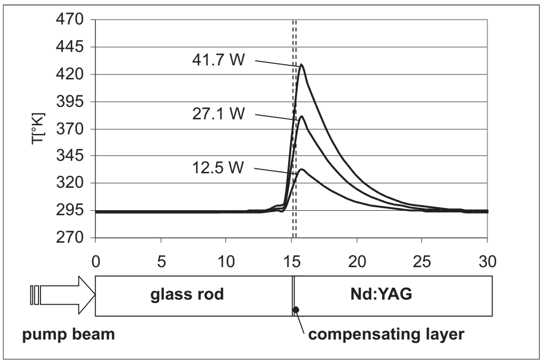

Figure 4. Simulation of the temperature distributions in the center of the rods for different values of the pump power (12.5 W, 27.1 W and 41.7 W resp.). The main part of the heat is deposited in the left end of the Nd:YAG rod, that's the point where the pump beam is focussed at.

conductivity of the liquid (0.138 W/cmK).

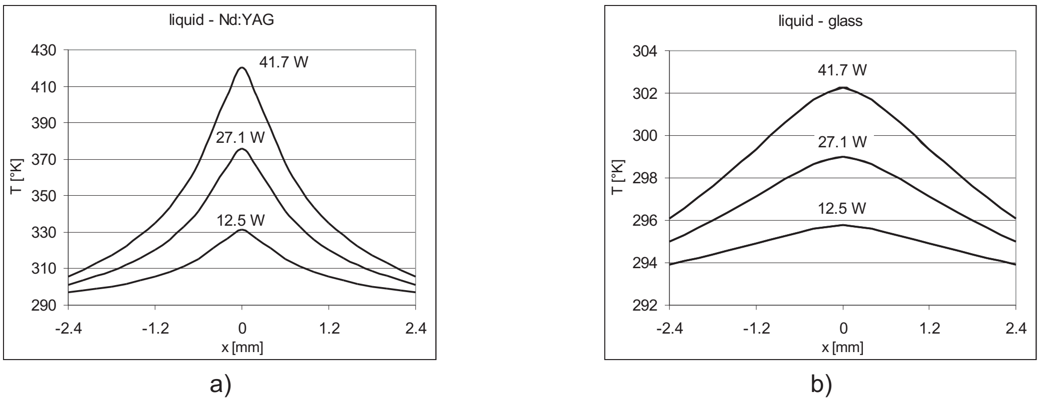

Figure 5. Simulation of the temperature profiles at the contact surfaces between the liquid layer and the rods for different values of the pump power (12.5 W, 27.1 W and 41.7 W resp.). a) Transition from liquid to Nd:YAG, b) from liquid to glass rod.

3. EXPERIMENTS

For the experiments, the laser rod was pumped with a collimated diode-laser beam @809 nm which was focussed through the glass rod and the compensating medium onto the end-face of the laser rod as shown in Fig. 1c). The two faces of the laser rod are AR coated (taking into account the refractive index of the compensating medium). The surface of the glass rod facing the compensating liquid is HR coated for the laser wavelength and AR for the pump beam. For the compensation we used the optical coupling fluid OCF-446 (by Nye Optical Products, USA). The thickness of the fluid layer was varied between 0.05 mm and 0.15 mm to find the optimal compensation. The Nd:YAG laser rod and the glass rod had a diameter of 5 mm and a length of 15 mm each. The resonator length was 40 cm.

The experimental setup is sketched in Fig. 6. The total dioptric power of the thermal lens induced in

the compensated laser was measured by means of a Mach-Zehnder interferometer with a HeNe laser @633 nm. The beam of the HeNe laser is enlarged with a telescope and split with a beam splitter (beam splitter (1)). One part of the beam passes the resonator as the other one is used as reference. With a second beam splitter (beam splitter (2)) the two beams are superimposed and produce interference fringes which are recorded by a CCD camera. Since the laser has to be pumped through one of the mirrors of the interferometer (mirror (3)), this mirror has to be AR coated for the pump wavelength. The output power of the laser was measured by a power meter.

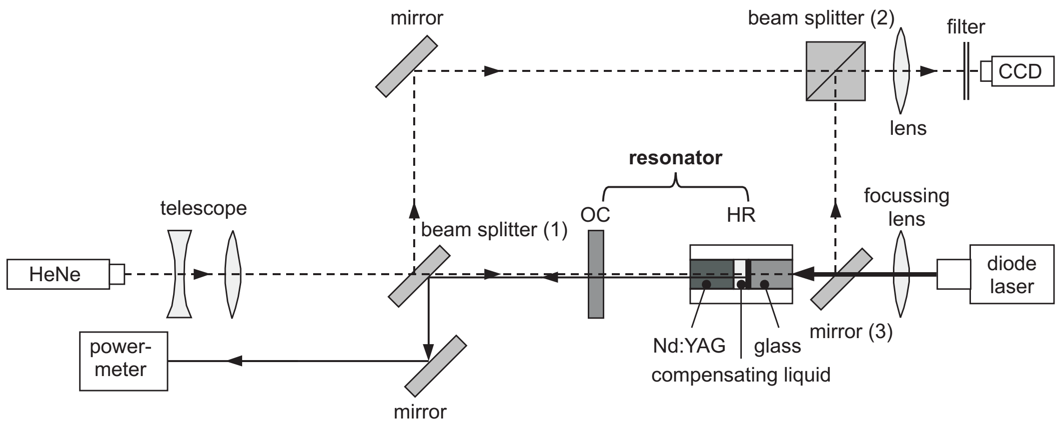

Figure 6. Experimental setup to measure the power and the thermal lens of the compensated laser. The beam of the pumping diode laser is represented by a bold arrow, the beam of the interferometer HeNe laser by a dashed line and the beam of the Nd:YAG laser by a solid line.

4. RESULTS

The dioptric power of the total thermal lenses (i.e. the dioptric power of the positive lens of the laser rod plus the negative one of the compensating liquid) was determined from the interference patterns. The results are shown in Fig. 7 together with the measured lenses of a laser without compensation for comparison. Due to photo-elastic effects occurring in the Nd:YAG rod and the glass rod the thermally induced lenses are different for radially and tangentially polarized light. As can be seen in the figure the compensation reduces the dioptric power of the total thermal lens by at least three times.

The reduction of the overall thermal lens caused by this self-adaptive compensation technique leads to an increase of the pump power range over which the resonator supports stable laser oscillation. This is illustrated with the measured input-vs.-output curves shown in Fig. 8. For these measurements the thickness of the compensating layer was varied between 0.05 mm and 0.15 mm as shown in the legend of the graph.

The figure shows that the stability range increases with increasing thickness of the layer of compensating liquid. With a 0.15 mm thick layer the laser operation was stable up to the maximum available pumping power of 28.6 W. Further it shows that all the slopes in Fig. 8 have a dip before the output power really breaks down. This is also due to the photoelastic effect mentioned above. Once the dioptric power of the thermal lens for radially polarized light reaches a value where the resonator gets unstable for this polarisation, the output power slightly breaks down. But though the resonator is still stable for tangentially polarized light the slope still increases until the stability limit for this polarization is reached as well. That is the point where laser operation completely stops.

Table 1 compares the slope efficiency of the uncompensated and the compensated laser and shows that it is increasing with thicker layers of the compensating liquid.

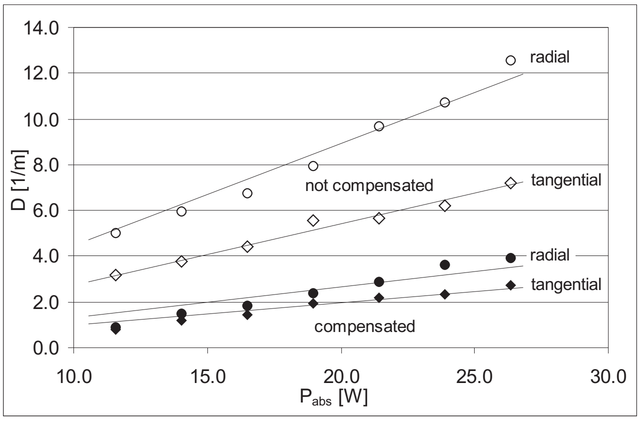

Figure 7. Dioptric power of the total thermal lens versus the power absorbed by the laser rod for an uncompensated (white) and a compensated laser (black) for radial and tangential polarization of the light resp. The thickness of the layer of compensating liquid was 0.15 mm.

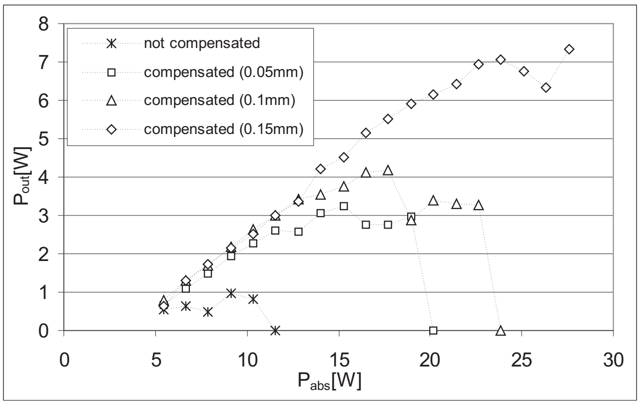

Figure 8. Output power versus absorbed power for a laser without compensation (asterisks) and for compensated lasers with layers of compensating liquid of 0.05, 0.1 and 0.15 mm.

All results presented above show that the best compensation was achieved with the thickest of the compensating layers we investigated. With a liquid layer of 0.2 mm the laser was unstable. This is most likely because of an over-compensation of the thermal lens. With the present set-up it was not possible to vary the thickness of the layer in steps smaller than 0.05 mm .

5. CONCLUSIONS AND OUTLOOK

In conclusion we have shown that thermal lenses in solid-state lasers can be compensated very effectively with thin layers of liquids with suitable properties. After successful experiments with side-pumped lasers[2, 3, 5, 6] we presented for the first time very promising experimental results for an end-pumped system.
According to the results with transversally pumped lasers[2] we can expect an even more significant

Table 1. Slope efficiency of the uncompensated and the compensated laser

uncompensated	0.16
compensating layer = 0.05 mm	0.27
compensating layer = 0.1 mm	0.30
compensating layer = 0.15 mm	0.39

compensation of the thermally induced lenses after further optimizations of the set-up presented here. The main issue is the thickness of the compensating layer which has to be set with a higher precision than currently possible with the present set-up.

ACKNOWLEDGMENTS

The authors acknowledge H. Glur for his great help with the finite element simulations.

REFERENCES

1. R. Weber, T. Graf, M. Schmid, and H. P. Weber, "Self-adjusting compensating thermal lens to balance the thermally induced lens in solid-state lasers," *IEEE J. Quant. Electron.* **36 6**, pp. 757–764, 2000.
2. T. Graf, E. Wyss, M. Roth, and H. P. Weber, "Laser resonator with balanced thermal lenses," *Opt. Comm.* **190**, pp. 327–331, 2001.
3. T. Graf, E. Wyss, M. Roth, and H. P. Weber, "Adaptive thermal optics in high-power laser resonators," in *Laser Resonators and Beam Control V (Photonics West, January 2002, San José, USA)*, *SPIE Proceedings* **4629**, 2002.
4. S. C. Tidwell, J. F. Seasmans, M. S. Bowers, and A. K. Cousins, "Scaling cw diode-end-pumped nd:yag lasers to high average powers," *IEEE J. Quantum Electronics* **28**, pp. 997–1009, 1992.
5. T. Graf, E. Wyss, M. Roth, and H. P. Weber, "Compensation of thermal lenses in high-power solid-state lasers," *Proceedings of IQEC-LAT 2002 (June 2002, Moscow, Russia)*, 2002.
6. E. Wyss, M. S. Roth, T. Graf, and H. P. Weber, "Thermo-optical compensation methods for high-power lasers," *IEEE J. Quantum Electronics* , to be published end of 2002.

Part 2

End-Pumped Nd:YAG Laser With Self-Adaptive Compensation of the Thermal Lens

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End-Pumped Nd:YAG Laser With Self-Adaptive Compensation of the Thermal Lens

Michelle S. Roth, Eduard W. Wyss, Thomas Graf, Heinz P. Weber

Abstract – **Thermally induced lenses are the most critical problem in the development of high-power solid-state lasers. To compensate for thermal lenses, we have been investigating self-adaptive compensation methods based on thermal effects themselves. Recently, we demonstrated a novel compensation scheme for transversally pumped lasers. This scheme has now been adapted to an end-pumped laser system. The reduction of the thermal lens has been simulated and measured experimentally. The experiments were carried out with a diode-pumped Nd:YAG laser with a maximum output power of 15.6W.**

Index Terms – **Adaptive optics, laser resonators, laser stability, laser thermal factors, liquids, Nd:YAG, thermooptic effects.**

I. Introduction

THE thermal lens in a pumped laser rod depends on the absorbed pump power P and the radius of gain r_p. The dioptric power of the thermal lens can be written as

$$D = \frac{D^* P}{\pi r_p^2}. \quad (1)$$

Neglecting birefringence and the end-effect, the specific dioptric power is given by

$$D^* = \frac{\eta}{2\kappa} \cdot \frac{dn}{dT}, \quad (2)$$

where η is the fraction of pump power converted to heat, κ the heat conductivity and dn/dT the thermal dispersion. The thermal effects are limiting the range of pump power over which the laser resonator supports stable oscillation. The stability range $\triangle P$ is inversely proportional to the specific dioptric power of the thermal lens in the laser rod [1]:

$$\triangle P = \frac{2\lambda r_p^2}{D^* w_0^2}, \quad (3)$$

where λ is the laser wavelength and w_0 the radius of the fundamental mode. Assuming that all modes with a radius smaller than the radius of gain r_p oscillate, the beam quality factor M^2 can be denoted as [2], [3]

$$M^2 = \frac{1}{2}\left(\frac{r_p^2}{w_0^2} + 1\right). \quad (4)$$

Inserting (4) into (3) gives

$$\triangle P = (2M^2 - 1)\frac{2\lambda}{D^*}. \quad (5)$$

In order to get good beam quality (i.e. low M^2) over a wide range of stable laser oscillation, D^* has to be as small as possible. In the following section, a way to reduce the total specific power D^* by self-adaptive compensation of the thermal lens of the laser is discussed.

II. Self-adaptive compensation schemes based on liquids

Thermal lensing in a laser rod can be compensated for by static methods such as an lens placed in the resonator (e.g., in [4]), but these techniques only correct the thermal lens exactly at one specific power and thus do not reduce the specific dioptric power D^*. As the thermal lens varies with the power of the laser, it is advantageous to use adaptive compensation methods. Recently, we have successfully demonstrated the compensation of thermally induced lenses in transversally pumped laser rods by means of a self-adaptive compensating element (CE) placed inside the laser resonator [5]. In a first approach, we have proposed to use a rod

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The authors are with the University of Bern, Institute of Applied Physics, CH-3012 Bern, Switzerland
(email: michelle.roth@iap.unibe.ch)
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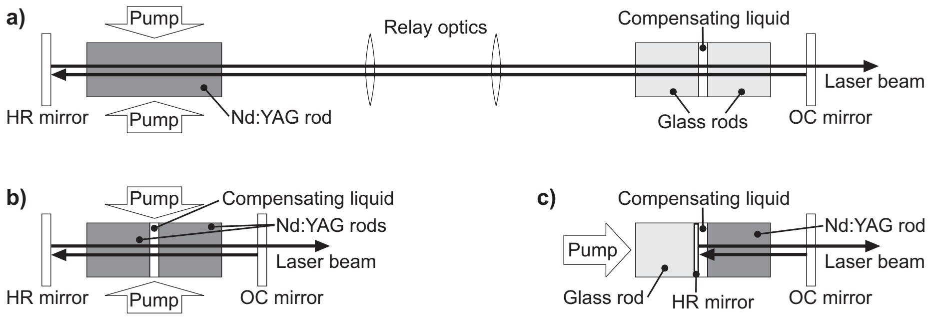


Figure 1: Compensation schemes. a) Transversally pumped laser with separate CE and relay optics. b) Transversally pumped laser with compensating liquid sandwiched between two laser rods. c) End-pumped pumped laser with compensating liquid sandwiched between laser rod and end mirror on a glass rod.

of a suitable material (e.g., phosphate glass) that absorbs a small fraction of the intracavity laser radiation to generate a power-dependent compensating lens. This negative thermal lens that is generated in the CE adaptively compensates for the varying positive lens in the laser rod (such as a transversally pumped Nd:YAG rod). In practice, it was found that it is difficult to find or to develop a material that meets all the required properties (such as thermal dispersion, absorption, heat conductivity, etc.) for an optimized thermooptical compensation. As a consequence, we developed a composite compensation scheme which comprises a thin liquid layer to generate the compensating lens [6]. The advantage of liquids is that they generally have a very strong thermal dispersion dn/dT, which means that only a thin layer and small heating powers are required to generate the desired lenses. In order to generate a power-dependent thermal lens in the CE, a radially oriented heat removal is required. This was achieved by filling the compensating liquid in a gap between two glass rods placed in a cooling mount. Due to this, the heat generated in the CE by the absorption of the intra-cavity laser radiation is removed mainly in radial direction which induces the desired power-dependent temperature profile.

In the original compensation scheme summarized above, the CE is arranged inside the resonator and the compensating lens has to be superimposed with the lens in the laser rod by means of relay optics as shown in Fig. 1 a). This set-up can be simplified by placing the compensating liquid layer directly at the location where it is needed. For transversally pumped lasers, the compensating layer is sandwiched in the middle between two laser rods as indicated in Fig. 1 b), [7]. With this, the temperature distribution in the laser rod is transferred to the compensating medium directly by the close heat contact. This compensation scheme can also be adapted for end-pumped lasers. In this case, the compensating liquid layer is placed between the pumped face of the laser rod and a glass rod that serves as the HR end-mirror as shown in Fig. 1 c). Again, the temperature distribution generated in the laser rod is transferred to the compensating layer by heat contact, leading to an optimum compensation of the thermally induced lens with varying laser power.

III. Thermal effects in end-pumped lasers

End pumping of solid-state lasers is a good method to achieve good beam quality. Due to the small pump beam radius it is much easier to produce fundamental-mode laser oscillation than in a side-pumped laser where the gain radius is much larger and allows higher-order modes to oscillate. But there are also some disadvantages in end pumping. In an end-pumped laser, the thermal lens is usually much stronger than in a transversally pumped laser with the same pump power. In a side-pumped laser, the pump power is distributed more or less homogeneously along the rod which leads to a parabolic temperature profile in radial direction. In an end-pumped laser, the pump beam radius is usually smaller than the radius of the rod and the pump power is concentrated in the central

region along the rod axis. This leads to a radial temperature profile that is parabolic in the central region and decays logarithmically toward the edges of the rod. If we assume a flat-topped pump profile, the temperature distribution can be described by the equation [4]

$$T(r) = T_0 + \frac{P_{abs}}{4\pi\kappa L} \cdot \begin{cases} -2ln\left(\frac{r_{pump}}{r_{rod}}\right) + 1 - \left(\frac{r}{r_{pump}}\right)^2, & r \leq r_{pump} \\ -2ln\left(\frac{r}{r_{rod}}\right), & r > r_{pump} \end{cases} \quad (6)$$

where T_0 is the temperature at the edge of the rod, P_{abs} the absorbed power, κ the heat conductivity and L the length of the rod. The radius of the laser rod is r_{rod} and the radius of the pump beam is r_{pump}.

In longitudinal direction, the temperature is higher at the pumped end of the rod and, according to Beer's law, decreases logarithmically toward the other end due to the absorption of the pump power. This very inhomogeneous temperature distribution in the laser rod leads to strong optical distortions caused by thermal effects.

IV. Numerical simulations

To examine the thermal behavior of the compensated laser rod, finite element simulations were carried out. In the first approach, the absorption of pump power in the glass rod was neglected as it is very small compared to the absorption in the Nd:YAG rod. Furthermore the divergence of the pump beam was neglected as well. The temperature distribution in the compensating unit (i.e., the laser rod, the compensating liquid and the glass rod, surrounded by the copper cooling-mount) was simulated for different thicknesses of the compensating layer and for different pump powers. As expected, the main part of the heat is deposited in the end of the Nd:YAG rod where the pump beam is focussed on. Although the temperature profile in the compensating liquid is mainly generated by heat conduction between the laser rod and the liquid, the absorption of intracavity laser radiation can not be neglected. Fig. 2 shows the simulated temperature profile along the longitudinal axis in the center of the rod for different values of the pump power.

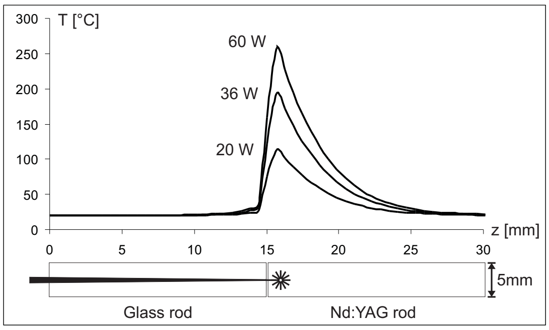


Figure 2: Simulation of the temperature distributions in the center of the rods for different values of the pump power (20 W, 46 W and 60 W resp.). The main part of the heat is deposited in the left end of the Nd:YAG rod, i.e. at the point where the pump beam is focussed at.

V. Experiments and results

For the experiments, the laser rod was pumped with two diode-lasers (809 nm) with a maximum output power of almost 40W each. The beams of the two diode-lasers were superimposed and focussed through the glass rod and the compensating medium onto the end of the laser rod by a collimating lens as shown in Fig. 3.

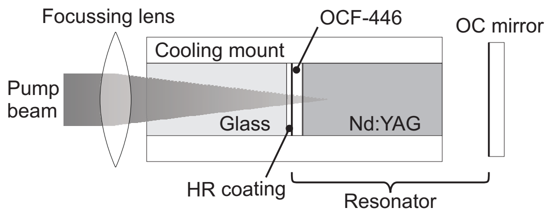


Figure 3: Schematic of the compensating unit.

The Nd:YAG laser rod and the glass rod had a diameter of 5 mm and a length of 15 mm each. The resonator length was 25 cm. The two faces of the laser rod were AR coated (taking into account the refractive index of the compensating medium). The surface of the glass rod facing the compensating liquid was HR coated for the laser wavelength. The two rods were mounted in a water-cooled copper mount. The gap between the rods could be varied by a micrometer screw, so that the thickness of the layer of the compensating fluid could be varied with an accuracy of about 1 μm. For the compensation, we used the optical coupling fluid OCF-446 by Nye Optical Products, which has a refractive in-

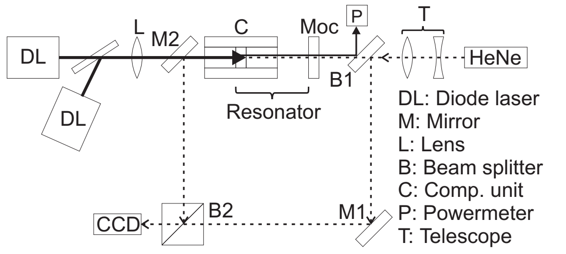


Figure 4: Experimental setup to measure the power and the thermal lens of the compensated laser. The beam of the two pumping diode lasers (DL) is represented by a bold line, the beam of the interferometer HeNe laser by a dashed line, and the beam of the Nd:YAG laser by a solid line.

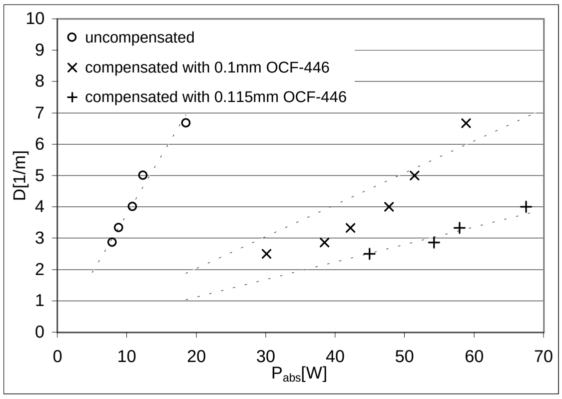


Figure 5: Dioptric power versus absorbed pump power. The dashed lines show the data calculated from the simulation results.

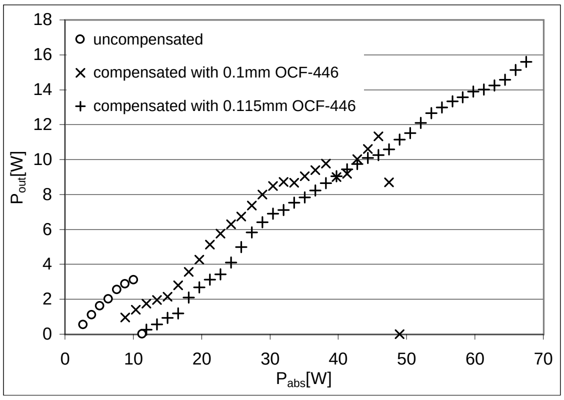


Figure 6: Output power versus absorbed pump power. Comparison between uncompensated and compensated laser.

dex of 1.46 (@ 589 nm) and a thermal dispersion of -3.4·10^{-4} K^{-1} [8]. The thickness of the fluid layer was varied between 50 μm and 150 μm to find the optimum compensation. The viscosity of OCF-446 is high enough (1.7 Ns/m according to [8]) that no convection occurs in such thin layers. To determine the optimum thickness it was set to a certain value and then the pump power was increased until the laser became unstable. Now the thickness of the compensating layer was also extended until the compensation was strong enough and the laser got stable again. This iterative process could be repeated several times until the optimum compensation was found. Once the optimum compensation was found, the thickness had not to be changed anymore.

The total dioptric power of the thermal lens induced in the compensated laser was measured by means of a Mach-Zehnder interferometer with a HeNe laser @633 nm. The setup is sketched in Fig. 4. The beam of the HeNe laser is enlarged by means of a telescope (T) and split with a beam splitter (B1). One part of the beam passes the resonator whereas the other one is used as reference. With a second beam splitter (B2), the two beams are superimposed and produce interference fringes which are recorded by a CCD camera. Since the laser has to be pumped through one of the mirrors of the interferometer (M2), this mirror has to be AR coated for the pump wavelength. The output power of the laser was measured by a power meter (P).

The experiments show that the total thermal lens in the laser resonator can significantly be reduced by the self-adaptive compensation. With a compensating layer of 100μm, the thermal lens was reduced by 4.3 times and with a layer of 115μm even by 8.7 times compared to the thermal lens in an uncompensated laser (Fig. 5).

According to (3), the reduction of the overall thermal lens leads to an increase of the pump power range over which the resonator supports stable laser oscillation. Fig. 6 shows the output power versus the absorbed pump power of the uncompensated laser compared to the compensated laser with two different thicknesses (100μm and 115μm, respectively) of the compensating liquid.

All measurements were done with a resonator with a length of 25cm. Without compensation, the pump power range over which the laser is stable is limited to about 10W. With the compensating layer of 100μm, the stability range could be in-

creased to about 50W and with the layer of 115μm, the laser was stable up to the maximum available pump power of about 70W. In all cases, the M^2 was measured to be not more than 1.9. The slope efficiency of the compensated laser is comparable to the slope efficiency of the laser without compensation.

VI. Conclusion

In this work, we present for the first time an end-pumped solid-state laser with self-adaptive compensation of the thermal lens. In a thin liquid layer heated by the adjacent laser rod, a defocusing lens is generated through direct heat contact. This power dependant lens compensates for the focusing thermal lens of the laser rod. In our experiments, we obtained a reduction of the total intracavity thermal lens of almost an order of magnitude. The reduced pump power dependance of the total dioptric power leads to a drastical increase of the stability range of the laser. The great benefit of the presented compensation scheme is the simplicity of this method, due to the exploitation of the thermo-optical effects the compensation is fully self-adaptive and does not need any external control.

References

[1] T. Graf, J. E. Balmer, R. Weber, and H. P. Weber, "Multi-Nd:YAG-rod variable-configuration resonator (VCR) end pumped by multiple diode-laser bars," *Optics Communications*, vol. 135, pp. 171–178, 1997.

[2] T. Graf, E. Wyss, and H. P. Weber, "Self-Adaptive Compensation for the Thermal Lens in High-Power Lasers," in *Proceedings of the ASSL*, ser. OSA TOPS, vol. 50, 2001, pp. 688–692.

[3] T. Graf and J. E. Balmer, "Laser beam quality, entropy and the limits of beam shaping," *Optics Communications*, vol. 131, pp. 77–83 (equations 30–33), 1996.

[4] S. C. Tidwell, J. F. Seamans, M. S. Bowers, and A. K. Cousins, "Scaling CW diode-end-pumped Nd:YAG lasers to high average powers," *IEEE Journal of Quantum Electronics*, vol. 28, pp. 997–1009, 1992.

[5] R. Weber, T. Graf, M. Schmid, and H. P. Weber, "Self-adjusting compensating thermal lens to balance the thermally induced lens in solid-state lasers," *IEEE Journal of Quantum Electronics*, vol. 36 6, pp. 757–764, 2000.

[6] T. Graf, E. Wyss, M. Roth, and H. P. Weber, "Laser Resonator with Balanced Thermal Lenses," *Optics Communications*, vol. 190, pp. 327–331, 2001.

[7] T. Graf, E. Wyss, M. Roth, and H. P. Weber, "Adaptive thermal optics in high-power laser resonators," in *Laser Resonators and Beam Control V (Photonics West, January 2002, San José, USA)*, ser. SPIE Proceedings, vol. 4629, 2002.

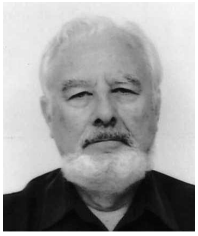
[8] "OCF-446 Optical Coupling Fluid: data sheet," Nye Optical Products, Fairhaven MA, USA.

Michelle S. Roth was born in Bern, Switzerland, in 1974. She studied physics, mathematics and ecology and received her Diploma in physics from the University of Bern, Bern, Switzerland in 2002. The research subject of her diploma thesis was on thermal effects in solid-state lasers. She is currently working toward the Ph.D. degree at the Institute of Applied Physics, University of Bern.
Her current activities includes the research for fluids that are convenient for the compensation of thermal lenses in high-power solid-state lasers.

Eduard W. Wyss was born in Bern, Switzerland, in 1971. He studied informatics, mathematics and physics at the University of Bern, Bern, Switzerland and at the University of Strathclyde, Glasgow, U.K. He received the M.Sc. and Ph.D. degrees in physics from the University of Bern in 2000 and 2003, respectively.
Currently he is a Postdoctoral Research Associate at the Institute of Applied Physics, University of Bern. His main research activities are the exploitation of thermo-optical effects for high-power laser resonators and the generation of radially polarized beams.

Thomas Graf was born in Lugano, Switzerland, in 1966. He received the M.Sc. degree in physics and the Ph.D. degree from the University of Bern, Bern, Switzerland, in 1993 and 1996, respectively.
As a Postdoctoral Research Associate he was engaged in research on high-power solid-state lasers with high beam quality, beam-shaping for diode-laser bars, and thermodynamics of optical systems at the University of Bern until 1997. He then joined the University of Strathclyde, Glasgow, U.K., where he was engaged in research on non-linear optics, passively mode-locked multi-Watt all-solid-state lasers and where he collaborated in an experiment on dipole traps for laser-cooled

atoms. In April 1999 he was appointed Head of the High-Power Lasers and Material Science Group, Laser Department, Institute of Applied Physics, University of Bern where he was awarded the *venia docendi* in 2001 and where he has been an Assistant Professor since April 2002. He is currently interested in high-power all-solid-state laser systems with adaptive resonators, novel fibre lasers with phase-locked core-arrays and in the generation of custom modes with intra-cavity graded-phase optics.
Prof. Graf serves as a board member of the Swiss Society for Optics and Microscopy (SSOM) and is a regular member of the Optical Society of America and the Swiss Physical Society.



Heinz P. Weber (M'72-SM'85-F'89)received the Diploma in Physics from Eidgenössische Technische Hochschule (ETH), Zürich, Switzerland, in 1964, and the Ph.D. degree from the University of Bern, Bern, Switzerland in 1968. His thesis was on generation and measurement of picosecond lightpulses, his main contribution was the discovery of the intensity-correlation method for time-duration measurement.
In 1969, he joined Bell Laboratories, Holmdel, NJ, where he was involved in research on integrated optics with organic materials and also in investigations of new rare-earth laser crystals. In 1975, he became Professor and Head of the Laser Department,e Institute of Applied Physics, University of Bern. Presently he is interested in modelocking and nonlinear effects in propagation of ultrashort lightpulses through optical fibers, in material processing, X-ray lasers, in diode-pumped solid state lasers with high output power and solid state and fiber lasers emitting in the 1-, 2- and 3-μm wavelength regions, as well as laser surgery employing such lasers.
Prof. Weber is member of the Swiss Academy of Technical Sciences, and a Fellow of the Optical Society of America.

Part 3

Self-Compensating Amplifier Design for CW and Q-Switched High-Power Nd:YAG Lasers

Submitted to

Optics Express

Self-Compensating Amplifier Design for CW and Q-Switched High-Power Nd:YAG Lasers

Michelle S. Roth, Valerio Romano and T. Feurer
Institute of Applied Physics, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland
michelle.roth@iap.unibe.ch

http://www.iap.unibe.ch

Thomas Graf
Institut für Strahlwerkzeuge, Universität Stuttgart, Pfaffenwaldring 43, D-70569 Stuttgart, Germany

Abstract

We experimentally demonstrate a self-adaptive compensation of the pump power dependent thermal lens in an Nd:YAG laser through a thin layer of a medium with a negative temperature dependence of the refractive index. The layer is thermally coupled to the laser rod and leads to a strikingly improved beam quality over a large stability range. The scheme allows for a scaling to high powers as well as pulsed-mode operation.

OCIS codes: (140.3480) Lasers, diode-pumped; (140.3530) Lasers, neodymium; (140.3540) Lasers, Q-switched; (140.3580) Lasers, solid-state; (140.6810) Thermal effects.

References and links

1. J. D. Foster and L. M. Osternink, "Thermal Effects in a Nd:YAG Laser," J. Appl. Phys. **41 (9),** 3656–3663 (1970).
2. W. Koechner, *Solid-State Laser Engineering*, (Springer, Berlin, 1999).
3. N. Hodgson and H. Weber, *Optical Resonators*, (Springer, Berlin, 1997).
4. Hansjürg Glur, Raphael Lavi and Thomas Graf, "Reduction of thermally induced lenses in Nd:YAG with low temperatures," IEEE J. Quantum Electron. **40 (5),** 499–504 (2004).
5. U. J. Greiner and H. H. Klingenberg, "Thermal lens correction of a diode-pumped Nd:YAG laser of high TEM_{00} power by an adjustable-curvature mirror," Opt. Lett. **19 (16),** 1207–1209 (1994).
6. A. V. Kudryashov, "Intracavity laser beam control," in *Laser Resonators II. 1999 San Jose, CA, USA*, A. V. Kudryashov, ed., Proc. SPIE **3611,** 32–41 (1999).
7. S. Jackel, I. Moshe and R. Lavi, "High performance oscillators employing adaptive optics comprised of discrete elements," in *Laser Resonators II. 1999 San Jose, CA, USA*, A. V. Kudryashov, ed., Proc. SPIE **3611,** 42–49 (1999).
8. D. C. Hanna, C. G. Sawyers and M. A. Yuratich, "Telescopic resonators for large-volume TEM_{00} mode operation," Opt. and Quantum El. **13 (6),** 493–507 (1981).
9. R. Koch, "Self-adaptive optical elements for compensation of thermal lensing effects in diode end-pumped solid state lasers - proposal and preliminary experiments," Opt. Commun. **140,** 158–164 (1997).
10. R. Weber, T. Graf and H. P. Weber, "Self-Adjusting Compensating Thermal Lens to Balance the Thermally Induced Lens in Solid-State Lasers," IEEE J. Quantum Electron. **36 (6),** 757–764 (2000).
11. E. Wyss, M. S. Roth, T. Graf and H. P. Weber, "Thermo-optical compensation methods for high-power lasers", IEEE J. Quantum Electron. **38 (12),** 1620–1628 (2002).
12. T. Graf, E. Wyss and H. P. Weber, "Self-adaptive compensation for the thermal lens in high-power lasers," in *Advanced Solid-State Lasers,* Ch. Marshall, ed., Vol. 50 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 2001), pp. 688–692.
13. M. S. Roth, E. Wyss, H. Glur, and H. P. Weber, "Generation of radially polarized beams in a Nd:YAG laser with self-adaptive overcompensation of the thermal lens," Opt. Lett. **30 (13),** 1665–1667 (2005).

1. Introduction

Many applications require high-power lasers with good beam quality over a wide range of output powers. However, the so-called thermal lens in solid-state lasers has a strong impact on the beam properties and deteriorate the beam quality [1, 2]. As the thermal lens increases with pump power, a good beam quality can only be achieved within an limited power range [3]. The maximum pump-power range ΔP for stable laser oscillation can be denoted as [4]

$$\Delta P = (2M^2 - 1)\frac{4\lambda}{D^*} \tag{1}$$

where M^2 is the beam propagation factor, and λ the laser wavelength. The quantity D^*, henceforth denoted as specific dioptric power, depends on thermo-optical material properties and the geometry. Equation (1) shows that for large values of D^* it is not possible to simultaneously achieve a wide stability range ΔP and a good beam quality, i.e. a low M^2. Hence, D^* has to be as small as possible, which can be achieved by compensating the thermal lens.

In principle, the thermal lens in a laser rod can be compensated for by static methods, such as an intracavity negative lens, but this will only correct the thermal lens exactly at one specific power. As the thermal effects are power-dependent it is advantageous to use adaptive compensation methods to counter them. A variety of possible methods has been reported, such as deformable mirrors [5, 6], moveable lenses [7], or telescopic resonators [8]. All of them require more or less sophisticated mechanical arrangements and active external control. A much simpler and very promising method is to take advantage of the thermal lens effect itself and to generate self-adjusting negative lenses in heated optical elements which can compensate for the thermal lenses in the laser material. In end-pumped lasers the compensating thermal lens can be generated through absorption of a small fraction of the pump beam in a resonator mirror or an additional intracavity element [9]. For high-power lasers, transverse pumping is usually preferred due to its simpler scalability. In this case the compensating element was heated by partial absorption of the intracavity laser radiation [10]. To generate a negative lens, the compensating element must possess a negative thermal dispersion dn/dT. Weber et al. [10] have proposed a compensating element made of the laser glass Schott LG-760 but further evaluation and numerical simulations revealed that glass-based compensation elements would only be suited for gain media with comparatively weak thermal lenses, such as Nd:YLF [11]. For laser materials that feature a stronger thermal lens, such as Nd:YAG, liquids are much better suited [11]. As liquids possess a strong negative thermal dispersion, already small amounts of heating power are sufficient to generate a negative thermal lens of the desired strength.

Here, we show that a thin layer of liquid, sandwiched in between two laser crystals can serve as a sufficiently strong self-adaptive element. Thermal heat diffusion from the crystals to the compensating element ensures that the temperature profile attains the correct spatial dependence. That is, the method works even in the absence of absorption, in contrast to previously published results [12]. We start by explaining the basic principles of self-adaptive compensation and then proceed with the experimental demonstration of the novel concept. We show that, first, this method is scalable to very high power levels and, second, it is suitable not only in continuous wave but also in pulsed mode operation, as it does not rely on absorbed laser power.

2. Self-Adaptive Compensation

In order to generate a thermal lens in the compensating element a radial temperature distribution is required that corresponds roughly to the radial temperature profile in the pumped and edge-cooled laser rod. This was recently achieved with the assembly depicted in Fig. 1.

The compensating element consisted of two BK-7 glass rods assembled in a water-cooled copper mount. The small gap (< 1 mm) between the two rods was filled with a liquid. The liquid was heated by absorption of a small fraction of the intracavity laser power. Due to the cooling the heat was dissipated in radial direction yielding the desired temperature profile. The power-dependant negative thermal lens

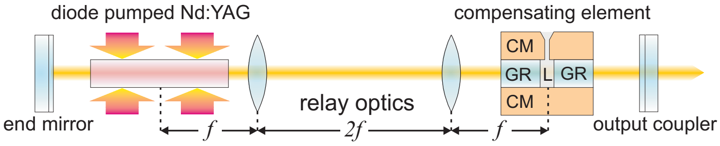


Fig. 1. Laser resonator with a self-adaptive compensating element. A thin layer of a liquid (L) is sandwiched in between two glass rods (GR) placed in a cooling mount (CM).

that was generated in the liquid was imaged to the positive thermal lens in the laser rod by means of an $f - 2f - f$ relay optics. This compensation scheme was successfully applied in several experiments [12, 13]. An alternative scheme, the so-called thermo-optically self-compensating amplifier (TOSCA), was theoretically analyzed [11], but has not been experimentally verified until now. A tremendous advantage of the TOSCA scheme is its extremely compact design. The thermal lens is compensated directly at its origin, in the laser rod. Hence, the additional intracavity element plus the relay optics are superfluous.

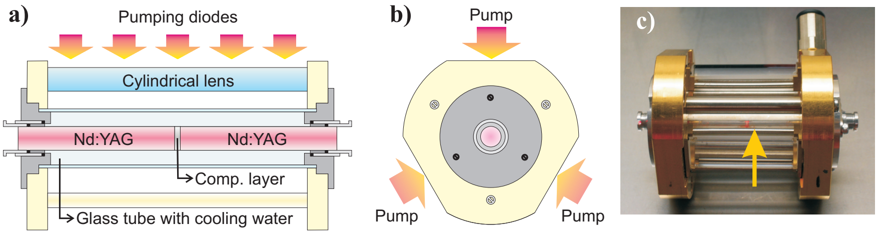


Fig. 2. TOSCA: a) side view and b) front view of the laser head. c) Image of the laser head (the arrow marks the position of the compensating gel disk).

Fig. 2 depicts the TOSCA assembly. A thin gel layer is sandwiched between two adjacent laser rods, which are mounted in a water-cooled glass tube. As the rods are homogeneously pumped from the side a radial temperature distribution is generated, leading to the well known thermal lenses in the rods. The temperature profile of the laser rods is transferred to the gel layer through heat contact. Owing to the negative dn/dT of the gel a negative thermal lens is formed, which compensates for the net positive lens of the laser rods.

3. Experimental Results and Discussion

Experiments were performed in three different configurations as shown in fig. 3. First, a resonator with a single laser head was equipped with the compensating element in order to demonstrate the TOSCA principle. Second, a resonator with two laser heads was used to test whether the scheme allows for scalability to high powers by inserting multiple heads. Third, the single head configuration was equipped with an acousto-optic modulator to operate the laser in pulsed mode. In all cases the output power, the dioptric power of the thermal lens, and the beam quality (M^2) were measured as a function of the pump power with and without compensation. In the latter case the two laser rods with the gel in between were replaced by a single rod with twice the length (70 mm). The effective dioptric power was measured by a Mach-Zehnder interferometer with a HeNe laser (633 nm). The beam quality was evaluated through measurements of the near and the far field beam profiles.

A single TOSCA was side-pumped by three stacks of laser diodes and the Nd:YAG rods have a diameter of 4 mm and a length of 38 mm each. As compensating media different silicones and polymers have been tested. The results presented below were attained with EFIRON® UVF Primary Coating P-100 (by Luvantix Co., Ltd.). The material has a refractive index of $n = 1.496$ and a thermal dispersion of

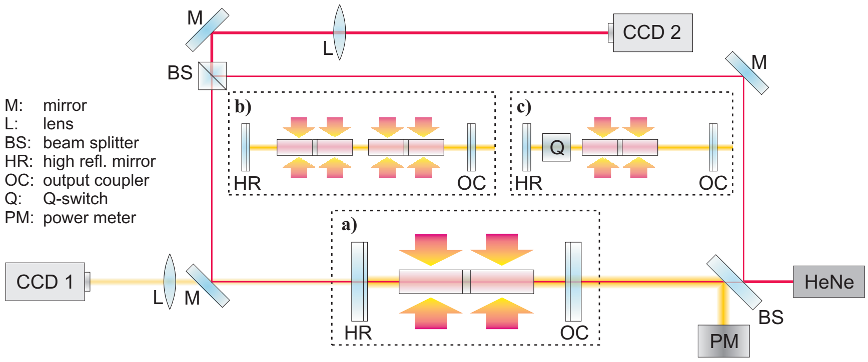


Fig. 3. Experimental setup to simultaneously measure the output power (PM), the beam quality (CCD 1), and the effective thermal lens (CCD 2) for three different configurations: a) single-head, cw; b) dual-head, cw; c) single-head, Q-switched

$dn/dT = -3.4 \cdot 10^{-4}\ \mathrm{K}^{-1}$. We would like to emphasize that the material is still not optimal as it exhibits a small residual absorption of 0.032 cm^{-1} at the laser wavelength. Therefore, the optimal thickness was always a tradeoff between a perfect compensation and a low additional intracavity loss. With these constrains the optimum thickness of the polymer layer was experimentally found to be between 0.3 mm and 0.6 mm. Also, the inner end-faces of the laser rods where originally AR coated for a refractive index of 1.416. As the refractive index of P-100 is slightly higher, i.e. 1.496, additional though small intracavity losses were present at each inner end-face.

3.1. Demonstration of the TOSCA Principle

In order to proof the TOSCA principle the single head laser was characterized with and without compensation. Figure 4 shows the output power of an uncompensated and two compensated laser rods with different thicknesses of gel layer. All measurements were performed with a 40 cm long symmetric resonator with plane mirrors. While the uncompensated laser reached its stability limit at a pump power of about 600 W, the laser with a compensating disk of 0.3 mm thickness supported stable operation up to 790 W with an efficiency of about 30%. With a 0.5 mm thick layer the efficiency was slightly reduced due to the larger absorption, but the laser was stable up to the maximum pump power of 850 W.

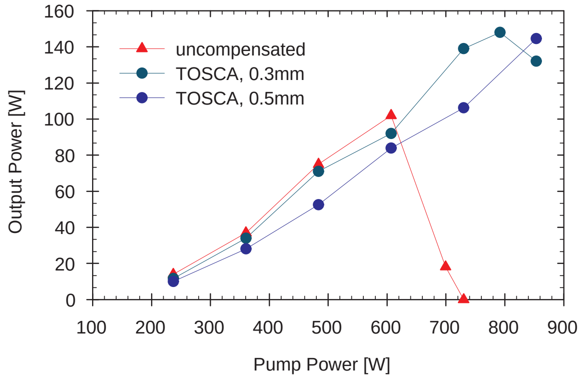


Fig. 4. Output power versus pump power of the single-head resonator with and without compensation.

The dioptric power was measured to be about 13.5 ± 0.3 dpt/kW for the uncompensated laser.

Inserting a 0.5 mm thick compensating layer reduced the dioptric power to about 7.3 ± 0.2 dpt/kW, i.e. the thermal lens was reduced by almost a factor of two.

One of the main purposes of compensating a thermal lens is to improve the beam quality. In order to compare the uncompensated laser to the TOSCA in terms of beam quality, further experiments had to be carried out with a much shorter resonator where the uncompensated laser is stable over the whole pump power range. The results for a 17 cm long resonator are depicted in fig. 5. The graph shows stable operation in both cases and the M^2 values versus output power. For the uncompensated laser the maximum output power was 194 W and the beam quality $M^2 = 54$. The TOSCA scheme reached a maximum output power of 160 W with $M^2 = 19$. Due to small additional losses (see above) the efficiency with compensation is somewhat lower than without. However, the beam quality shows a striking improvement by almost a factor of 3.

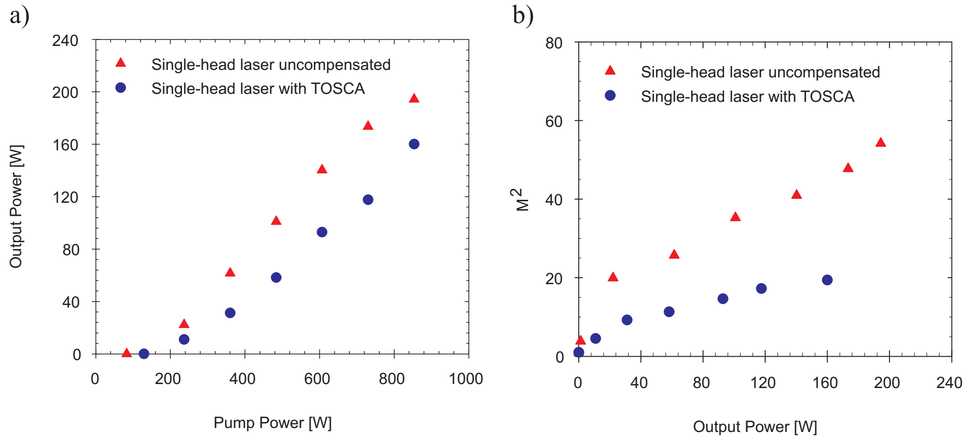


Fig. 5. a) Output power versus pump power and b) M^2 versus output power of the single-head resonator with and without compensation.

3.2. *Scalability to High Power Levels*

In order to scale the system to higher output powers a second TOSCA amplifier head was inserted into the resonator, increasing the total resonator length to 26 cm. Both laser heads were identical and were separated by 40 mm. The best performance was observed for a compensating layer of 0.3 mm in each laser head.

Figure 6a) shows the output power versus the pump power of the compensated single-head and the compensated dual-head resonator. The efficiency of the dual-head laser is slightly decreased compared to the single-head laser, mostly because of the difficulties in aligning the two heads, i.e. four laser rods. Nevertheless, the maximum output power of the single-head TOSCA of 158 W was almost doubled to 303 W. Figure 6b) shows that the good beam quality was maintained to the highest pump power, indicating that the TOSCA principle can be scaled to high power levels. Even at the highest output power of 303 W the M^2 is not higher than 25 whereas the uncompensated laser exhibits an M^2 of more than 25 already at output powers around 55 W.

3.3. *Q-Switch Operation*

To test the TOSCA principle for pulsed operation the resonator was equipped with an acousto-optical Q-switch. The repetition rate of the Q-switch was 9.7 kHz. Again a symmetric plane-plane resonator was used but because of the extra element its length had to be extended to 49 cm. In accordance with the results presented above, the uncompensated laser became unstable at high pump powers. Using the TOSCA (thickness 0.5 mm) the laser could be operated in a stable regime over the whole power

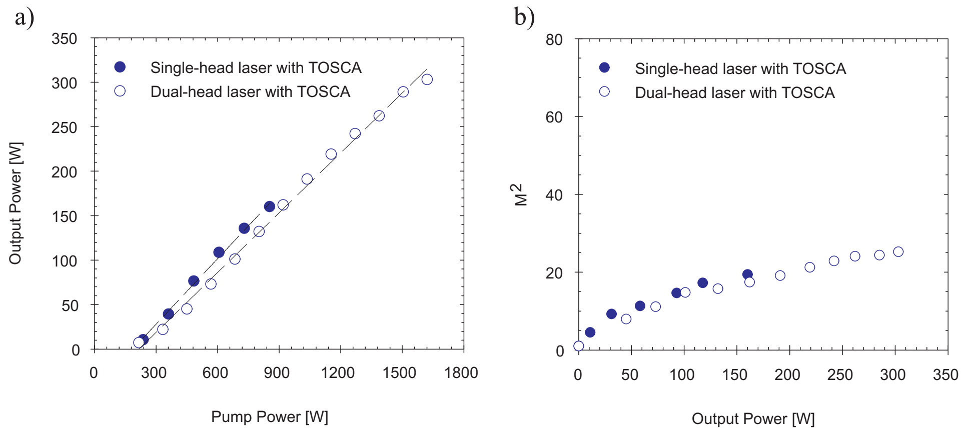


Fig. 6. Scaling of the output power through multiple but compensated laser heads. a) Output power and b) M^2.

range that was available. Note, in pulsed mode operation the slightest impurity or surface contamination caused a power absorption high enough to destroy the compensating layer.

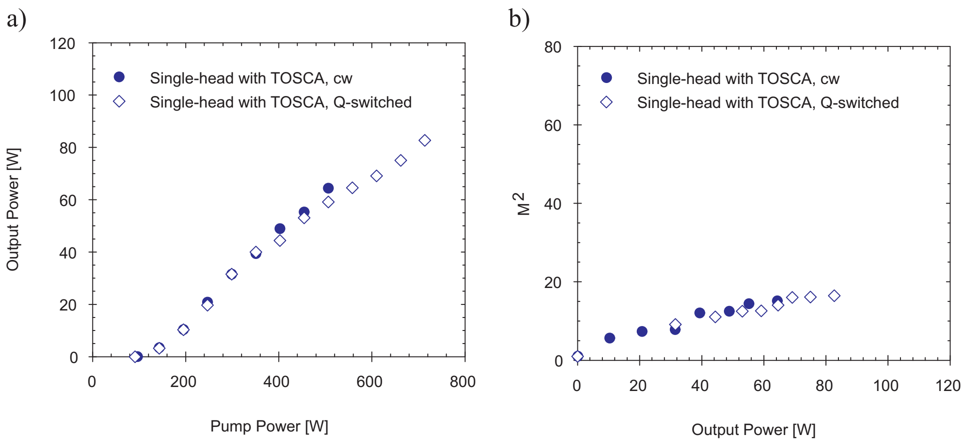


Fig. 7. a) Output power versus pump power and b) M^2 versus output power of the single-head resonator in cw and pulsed operation.

Figure 7a) shows the output power as a function of the pump level. At a pump power of 710 W the average output power was 83 W. Pulse durations of approximately 80 ns (FWHM) were measured, yielding a maximum pulse energy of 8.6 mJ and a maximum peak power of 107 kW. Figure 7b) emphasizes that there is no significant degradation of the beam profile in pulsed mode. The measured values correspond very well to the ones obtained in cw mode.

4. Conclusions

We have experimentally demonstrated the principle of a thermo-optically self-compensating amplifier. The TOSCA setup is very compact and entirely self-adaptive. The compensation reduces the thermal lens leading to a larger stability range as well as to a significant improvement of the beam quality. Within the limits of the material properties, we were able to show scalability to high powers and pulsed mode operation.

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Part 4

Dual-Head High-Power Nd:YAG Laser with Thermo-Optically Self-Compensating Amplifiers

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Dual-Head High-Power Nd:YAG Laser with Thermo-Optically Self-Compensating Amplifiers

Michelle S. Roth, Eduard W. Wyss and Valerio Romano

Institute of Applied Physics, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland
michelle.roth@iap.unibe.ch

Thomas Graf

Institut für Strahlwerkzeuge, University of Stuttgart, Pfaffenwaldring 43, D-70569 Stuttgart, Germany

Abstract

Thermal effects can be exploited to generate adaptive optical devices which compensate for thermal lenses in solid-state lasers. The thermo-optically self-compensating amplifier (TOSCA), consisting of a liquid layer sandwiched between two laser rods, is a very promising concept due to its simple and compact design. We present the application of the TOSCA scheme in a dual-head Nd:YAG laser producing an output power of more than 300W.

OCIS codes: : (140.3580) Lasers, solid-state; (140.6810) Thermal effects.

Introduction

Thermally induced optical distortions in the gain material are one of the most critical issues in high-power solid-state lasers since they severely limit the power range and negatively affect the beam quality of the laser. As these thermal effects are power-dependent it is advantageous to use adaptive compensation methods to counter them. There is a wide range of possible means, such as deformable mirrors [1, 2], moveable lenses [3] or telescopic resonators [4], but all of them require more or less sophisticated mechanical arrangements and active external control. A much simpler and therefore very promising method is to exploit the thermal effects themselves to generate self-adjusting lenses based on liquids or gels with negative thermal dispersion, which can compensate for the thermal lenses in the laser material [5]. Several compensation schemes based on this method have already successfully been tested in experiments [6, 7]. One of them, the so-called thermo-optically self-compensating amplifier (TOSCA) has recently been demonstrated in a Nd:YAG laser with a maximum output power of about 160W [8]. Here we show how the laser can be scaled up to higher output powers by the use of a second TOSCA unit.

The Thermo-Optically Self-Compensating Amplifier (TOSCA)

One of the great advantages of the TOSCA is its very compact design. A thin layer of a rubber-like gel is sandwiched between two adjacent laser rods mounted in a water-cooled glass tube. As the rods are homogeneously pumped from the side a radial temperature distribution is generated, leading to thermal lenses in the rods. The temperature profile of the laser rods is transferred to the gel layer by heat contact. Due to the negative thermal dispersion of the gel a negative thermal lens is formed, which compensates for the (positive) lenses of the laser rods. In order to scale the laser system up to higher output powers a second TOSCA laser head was inserted into the resonator. Both laser heads are identical; the gap between them is 40mm. Each head is side-pumped by three stacks of laser diodes.

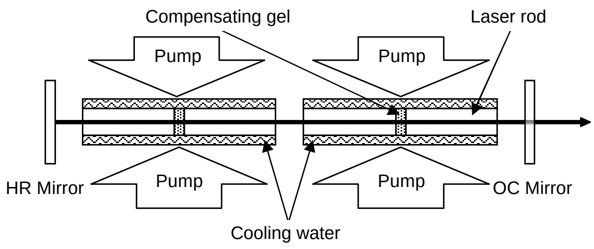

Figure 1: Sketch of the dual-head TOSCA set-up.

The Nd:YAG laser rods have a diameter of 4mm and a length of 38mm each. A sketch of the set-up is shown in Fig. 1.:

As compensating media silicones and polymers have been tested. The results presented below were attained with EFIRON® UVF Primary Coating P-100 (by Luvantix Co., Ltd.), a polymer material originally made for fiber coatings. The material has a refractive index of n=1.496 and a thermal dispersion of dn/dT=-3.4·$10^{-4}K^{-1}$ (Nd:YAG: dn/dT=7.3·$10^{-6}K^{-1}$). The optimum thickness of the polymer layer was experimentally found to be around 0.3mm.

Experimental Results

For comparison and characterization experiments were performed with four different set-ups: a single and a dual-head laser, both of them either without compensation of the thermal lens or with the TOSCA scheme. Each laser head was transversally pumped from three sides with diode stacks providing a maximum pump power of about 280W each. Thus the maximum pump power available was 810W for the single-head and 1620W for the dual-head laser. The resonator with one laser head had a total length of 20cm, the dual-head resonator was 26cm long. All experiments were done with symmetric plane-plane resonators. The results in Fig. 2. illustrate the reduction of the overall thermal lens in the self-compensated laser resonator.

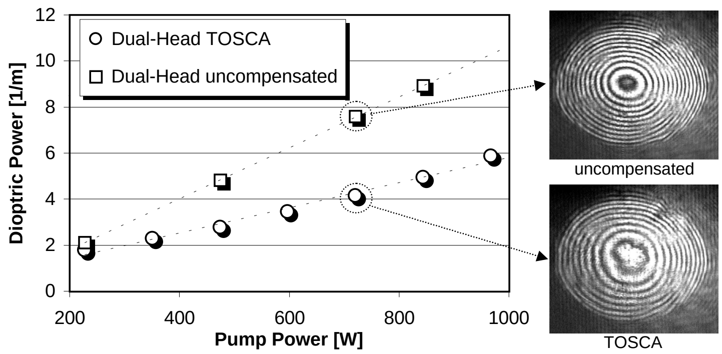

Figure 2: Dioptric power of the total thermal lens; the interference patterns on the right illustrate how the lens is reduced by the TOSCA.

The dioptric power was measured in a Mach-Zehnder interferometer with a HeNe laser @633nm. Two examples of the interference patterns are shown in Fig. 2. Compared to the uncompensated resonator the slope of the thermal lens is reduced almost by a factor of 2 with the TOSCA.

The principal intention of our experiments was to scale up the power from the single-head TOSCA system. Fig. 3. shows the output power versus the pump power of the single-head and the dual-head

resonator with the TOSCA. With the dual-head laser the efficiency is slightly decreased compared to the single-head laser. One of the reasons is the fact that with our set-up it was very difficult to get the two heads properly aligned. Nevertheless the maximum output power of the single-head TOSCA (158W) was almost doubled by the dual-head laser (303W).

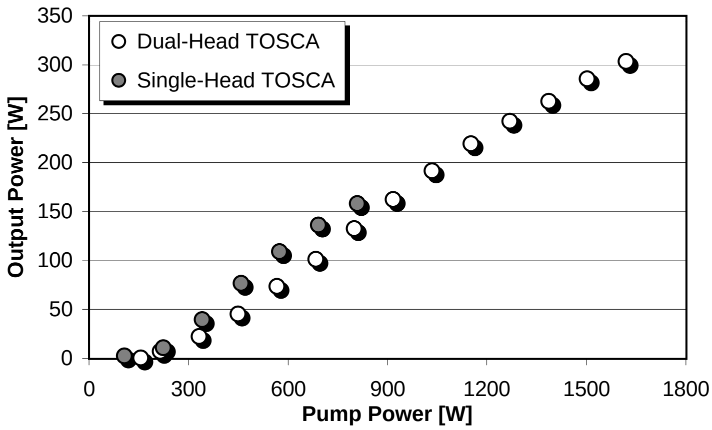

Figure 3: Output power versus pump power, comparison of the single-head and the dual-head TOSCA.

Compared to the uncompensated dual-head laser the efficiency of the dual-head TOSCA system is about 25% lower. On one hand this is due to absorption losses occurring in the compensating medium. On the other hand, the difficulties with the alignment of the two heads mentioned above cause more problems with the TOSCA heads than with the uncompensated ones as each TOSCA head consists of two rods, so there are actually four rods which have to be properly aligned. It can be assumed that more elaborated construction of the mount of the laser heads would ameliorate the efficiency of the dual-head laser system.

One of the main purposes of compensating for thermal lensing is to improve the beam quality of the laser. In order to characterize the laser beam quality, we determined the beam propagation factor (M^2). Fig. 4. represents the M^2 values with respect to the laser output power.

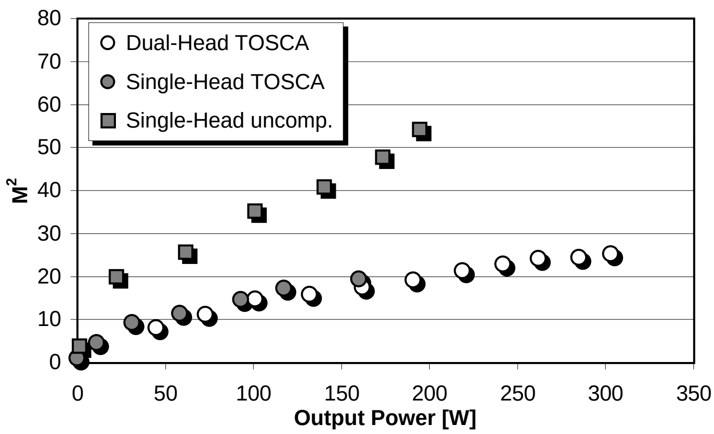

Figure 4: M^2 versus output power: comparison between TOSCA (dots) and uncompensated laser (squares).

This figure clearly points out the impact of the TOSCA. Without compensation, the M^2 increases

rapidly and reaches a value of 54 at an output power of not even 200W. At comparable output power the M^2 of the compensated laser (dual-head TOSCA) is still below 20, which gives a slope of ∼0.06/W output power whereas the slope for the uncompensated laser is about 0.19/W. At the maximum output power of the dual-head TOSCA laser the M^2 is 25.2.

Conclusions

In this work we have demonstrated that the principle of the thermo-optically self-compensating amplifier (TOSCA) can be implemented in a dual-head laser in order to achieve higher output power. The TOSCA set-up is very simple and compact and entirely self-adaptive. Thanks to the compensation the dioptric power of the thermal lens could be reduced and thus the beam quality is clearly improved.

Acknowledgments

The authors acknowledge Eva Krähenbühl for technical assistance. This work was supported in part by the Swiss Comission for Technology and Innovation (CTI).

References

[1] U. J. Greiner and H. H. Klingenberg, "Thermal lens correction of a diode-pumped Nd:YAG laser of high TEM_{00} power by an adjustable-curvature mirror," Optics Letters **19 (16),** 1207–1209 (1994).

[2] A. V. Kudryashov, "Intracavity laser beam control," in *Laser Resonators II. 1999 San Jose, CA, USA*, SPIE Proceedings 3611, (SPIE - Int. Soc. Opt. Eng, USA, 1999), pp. 32–41.

[3] S. Jackel, I. Moshe and R. Lavi, "High performance oscillators employing adaptive optics comprised of discrete elements," in *Laser Resonators II. 1999 San Jose, CA, USA*, SPIE Proceedings 3611, (SPIE - Int. Soc. Opt. Eng, USA, 1999), pp. 42–49.

[4] D. C. Hanna, C. G. Sawyers and M. A. Yuratich, "Telescopic resonators for large-volume TEM_{00} mode operation," Opt. and Quantum El. **13 (6),** 493–507 (1981).

[5] T. Graf, E. Wyss, M. S. Roth and H. P. Weber, "Laser resonator with balanced thermal lens", Opt. Comm. **190,** 327–331 (2001).

[6] E. Wyss, M. S. Roth, T. Graf and H. P. Weber, "Thermo-optical compensation methods for high-power lasers", IEEE J. Quantum Electron. **38 (12),** 1620–1628 (2002).

[7] M. S. Roth, E. Wyss, T. Graf, H. P. Weber, "End-pumped Nd:YAG laser with self-adaptive compensation of the thermal lens", IEEE J. Quantum Electron. **40 (12),** (2004).

[8] M. S. Roth, T. Graf, H. P. Weber, "High-Power Nd:YAG Laser with Thermo-Optically Self-Compensating Amplifier," in *EPS-QEOD Europhoton Conference on Solid-State and Fiber Coherent Light Sources 2004, Lausanne, Switzerland*, Europhysics Conference Abstracts, Vol. 28C, paper FrB3.

Part 5

Generation of radially polarized beams in a Nd:YAG laser with self-adaptive over-compensation of the thermal lens

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Generation of radially polarized beams in a Nd:YAG laser with self-adaptive overcompensation of the thermal lens

Michelle S. Roth, Eduard W. Wyss, Hansjuerg Glur, and Heinz P. Weber

Institute of Applied Physics, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland

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Thermal effects such as lensing and birefringence negatively affect the beam quality and limit the power range of solid-state lasers. Self-adaptive overcompensation of the thermal lens is an answer to this problem. It provides a laser system with good beam quality and large stability range. Because the focal length of the thermally induced lens is different for the radial and the tangential polarization, overcompensation can be used to discriminate these two polarizations. Exploiting this method, we demonstrate the generation of radially polarized beams in a self-adaptively overcompensated high-power Nd:YAG laser with an output power of 155 W and an M^2 of less than 10.

OCIS codes: 140.0140, 140.3530, 140.6810.

The formation of a thermally induced lens and birefringence occurring in solid-state laser media upon optical excitation lead to major problems in high-power lasers because these thermal effects severely limit the power range of stable operation and negatively affect the beam quality of the laser. The disturbing effect of the induced lens can be compensated for by modifying the optical resonator, e.g., by incorporating a negative lens or using adaptive mirrors.[1] A self-adaptive approach availing the thermal effects to generate a negative lens in a medium with negative thermal dispersion leads to laser systems that show good beam quality and stable laser oscillation over an almost unlimited power range.[2–4] This technique could even be improved by slightly overcompensating the thermal lens.[5] In this Letter we show how this self-adaptive overcompensation can be exploited to generate radially polarized laser emission.

In an axially symmetric arrangement, such as a laser rod, the thermally induced birefringence leads to locally varying birefringence resulting in a situation where linearly polarized radiation gets modified in a pump-power-dependent rather unpredictable way.[6,7] However, owing to the radial symmetry, radially or tangentially polarized radiation is unaffected in polarization. From this it follows directly that modes of this type are unaffected by the induced birefringence. Namely, because of the thermal stress in a heated laser rod, $C_{r,\phi}$, which is a function of the photoelastic coefficients of the material, has two different values for radially (r) and tangentially (ϕ) polarized light. Thus the focal length of the thermal lens also exhibits two different values depending on the polarization. Neglecting the so-called end effect, the focal length of a laser rod with a radius r_{LR} and a refractive index n_0 can be written as[8]

$$f_{r,\phi} = \frac{\kappa \pi r_{LR}^2}{P \eta_{heat}} \left(\frac{1}{2} \frac{dn}{dT} + \alpha C_{r,\phi} n_0^3 \right)^{-1}, \qquad (1)$$

where κ is the thermal conductivity, η_{heat} is the fraction of the pump power P converted to heat, and α is the coefficient of thermal expansion. For Nd:YAG these material parameters are the following:[8] κ=10.46 W/(m·K), η_{heat}=0.344, dn/dT=7.3×10^{-6}/K, α=7.5×10^{-6}/°C, C_r=0.017, C_ϕ=-2.523×10^{-3}, and n_0=1.82. Introducing these parameters into eq. (1) results in dioptric power $D_{r,\phi} = f_{r,\phi}^{-1}$ for a rod radius of r_{LR}=2 mm being 11.6 diopters/kW for the radial polarization and 9.5 diopters/kW for the tangential polarization. This bipolar lensing can be exploited to make a distinction between radial and tangential polarization.[9] The method presented in Ref. 9 led to a remarkably low M^2; however, the authors note that it only tolerates

pump-power variations of ±5%. In contrast, using a self-adaptively overcompensated resonator allows one to work in a rather unlimited range of pump powers.

To compensate for the (focusing) thermal lens of the laser rod, a self-adaptive compensating element (CE) comprising a thin layer of a gel or liquid is placed within the resonator. This element is heated by absorption of a small amount of the intracavity radiation and, owing to the negative thermal dispersion of the gel or the liquid, a defocusing lens is generated. With appropriate thickness of the layer the absolute value of the dioptric power of this lens matches the dioptric power of the lens in the laser rod and thus the overall lens in the resonator sums to zero. But, because thermally birefringent materials such as Nd:YAG have two different values of dioptric power for r and ϕ polarization, the lens is negated only for one of these polarizations. Taking advantage of this, we are able to generate radially polarized radiation with our self-adaptive compensation technique.

A descriptive way to illustrate the principle of our method is the stability space diagram as introduced in Ref. 10. Figure 1 shows the calculated stability space for the resonator used in our experiments as it is sketched in Fig. 2. The diagram shows the dioptric power of the CE versus the pump power. Because of the birefringence, the stability limits for the two polarizations (r and ϕ) are different. In Fig. 1 the stability limits for the radial polarization are plotted as dashed lines, in the area between these two dashed lines the radial polarization is stable. Correspondingly the tangential polarization is stable in the area limited by dashed-dotted lines. In the region where both areas overlap, both polarizations are stable (white region). In the spotted area, only the radial polarization and, in the hatched area, only the tangential polarization is stable. In the gray shaded regions they are both unstable.

With increasing pump power the overcompensated laser traverses the stability space diagram. Three different stages can be distinguished. In the first stage (I) below the laser threshold no compensating lens is generated in the CE; therefore the laser follows a horizontal line at 0 diopters. Once it has passed the threshold (at about 140 W for our laser parameters) the CE becomes effective, and thus in the second stage (II) the laser traverses the zone where both polarizations are stable (white area), followed by the region where only the r polarization is still stable (spotted area), until it reaches the stability limit (dashed line), also of the radial polarization, at a pump power of about 420 W. At this point, the beginning of the third stage (III), the effect of the overcompensation arises. As the laser exceeds the stability limit and enters the unstable region (gray shaded area), diffraction losses prevail, leading to a decrease in the intracavity laser power. Because the dioptric power of the CE depends directly on the intracavity power, it also decreases, thus bringing the laser back into the stable region. Consequently, the intracavity power will increase until the laser becomes unstable again. This process recurs periodically, locking the laser close to the stability limit in a dynamic equilibrium where it stays up to the maximum pump power. Since the ϕ polarization is not stable in this region, the laser emission is radially polarized.

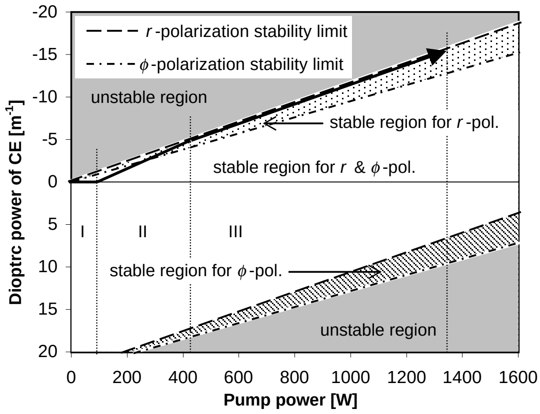

Fig. 1. Stability space diagram with stability limits for both radial and tangential polarization: the overcompensated laser traverses the diagram as indicated by the bold arrow, passing three different stages marked I – III.

To verify the theoretical considerations, experiments were performed with a nearly symmetric plane–plane resonator. The setup is sketched in Fig. 2.

The amplifier is a Nd:YAG laser rod with a radius of r_{LR}=2 mm and a length of L_{LR}=200 mm. The rod is transversally pumped by three diode laser stacks. The CE consists of two BG7 glass rods of a diameter of r_{GR}=3 mm and a length of

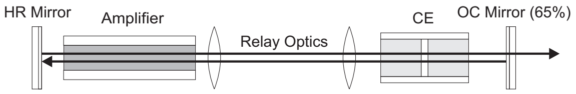

Fig. 2. Set-up.

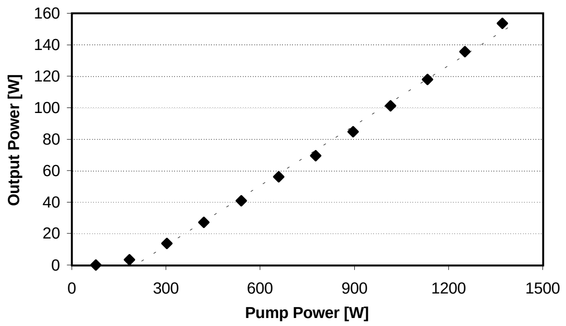

Fig. 3. Output power versus pump power.

L_{GR}=15 mm each and a thin layer of a compensating material sandwiched in between. A f-2f-f relay optics optically superimposes the compensating layer in the CE with the center of the laser rod.

Several materials have been tested for the compensation (a detailed list can be found in Ref. 3); the results presented in this Letter were attained with Sylgard 184, a silicone elastomer by Dow Corning. Whereas some of the liquid compensating materials exhibited degradation at high output powers, Sylgard 184 was not affected even at the highest operation power levels. The optimum thickness of the silicon layer was experimentally found to be around 1 mm. Thicker layers enhance the overcompensation but decrease the output power, owing to stronger absorption of the intracavity power. If the layer is too thin (i.e.,<1 mm) the thermal lens of the laser rod is no longer overcompensated, and thus the beam is not radially polarized.

Figure 3 shows the measured laser output power versus the pump power. At the maximum available pump power of about 1370 W the output power is measured to be 155 W.

For inspection the laser beam was imaged onto a CCD camera either by a 2f–2f image to see the near-field intensity distribution or a f–f image to see the far-field intensity distribution. To analyze the polarization, a linear polarizer was placed in front of the CCD camera. Figure 4 shows the near-field distribution of the laser beam at a pump power of 1000 W, recorded without the polarizer and with the polarizer oriented in the vertical, diagonal, and horizontal directions.

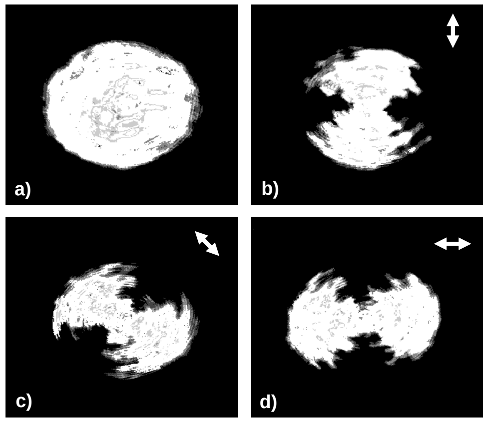

Fig. 4. Nearfield intensity distribution of the laser beam at an output power of 100W: a) without polarizer, b) polarizer in vertical, c) in diagonal and d) in horizontal position.

As can be gathered from the pictures in Fig. 4, the beam is not entirely radially polarized, most likely because of inhomogeneities in the pump distribution. The degree of radial polarization was determined from the measurements by calculating the angular correlation of the intensity distribution after the linear polarizer, once in the horizontal and once in the vertical direction. The results of the calculations are displayed in Fig. 5 along with beam propagation factor M^2.

The diagram shows that the laser reaches the stability limit of the tangential polarization (dashed line) at an output power of about 24 W (corresponding to a pump power of 390 W). Above this limit the proportion of the radial polarization in the laser beam is more than 80% (average, 83.7%). There is also an obvious bend in the increase of the M^2 value: At low output powers it rises quickly to a value of 6 at P_{out}=24 W, but then it remains almost constant and is less than 10 at the maximum output power of 155 W. This bend is a typical indicator that the laser passes the stability limit at about 24 W of output power. M^2 might be reduced by means of an aperture or exploitation of the aperture effect of the laser rod

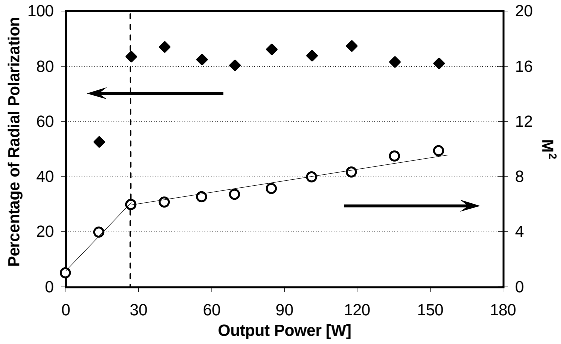

Fig. 5. Degree of radial polarization (black diamonds) and beam propagation factor M^2 (white circles) versus the output power of the laser. The vertical, dashed line marks the stability limit of the ϕ-polarization.

(e.g., in a long resonator), but this would lead to losses and thus lower the efficiency.

radially polarized laser beams by self-adaptive overcompensation of the thermal lens and exploitation of the thermally induced birefringence. The setup with a quasi-symmetric planeplane resonator and a compensating element is simple and entirely self-adaptive. Thanks to the compensation of the thermal lens the resonator is stable over a large power range, delivering radially polarized radiation with good beam quality.

M. S. Roth's e-mail address is michelle.roth@iap.unibe.ch

References

1. U. J. Greiner and H. H. Klingenberg, Opt. Lett. **19,** 1207–1209, 1994.
2. R. Weber, Th. Graf, M. Schmid and H. P. Weber, IEEE J. Quantum Elect. **36,** 757–764 (2000).
3. E. Wyss, M. S. Roth, Th. Graf and H. P. Weber, IEEE J. Quantum Elect. **38,** 1620–1628 (2002).
4. M. S. Roth, E. Wyss, T. Graf, H. P. Weber, IEEE J. Quantum Elect. **40,** 1700–1703 (2004).
5. E. Wyss, Th. Graf and H. P. Weber, IEEE J. Quantum Elect., accepted for publication in the May 2005 issue.
6. W. Koechner and D. K. Rice, IEEE J. Quantum Elect. **6,** 3656–3663 (1970).
7. J. D. Foster and L. M. Osterink, J. Appl. Phys. **41,** 3656–3663 (1970).
8. W. Koechner, *Solid-State Laser Engineering*, (Springer, 1999).
9. I. Moshe, S. Jackel and A. Meir, Opt. Lett. **28,** 807–809 (2003).
10. E. Wyss, Th. Graf and H. P. Weber, in ALT'02, vol. 5147 of SPIE Proceedings, 2002.

Appendix A

End-pumped Nd:YAG laser with self-adaptive compensation of the thermal lens

Conference Abstract

CLEO/Europe - EQEC 2003

Munich, Germany, 23-26 June 2003

End-pumped Nd:YAG laser with self-adaptive compensation of the thermal lens

M. S. Roth, Th. Graf and H. P. Weber
University of Bern, Institute of Applied Physics, Sidlerstrasse 5, CH-3012 Bern, Switzerland
michelle.roth@iap.unibe.ch

Our well approved fluid-based compensation method for thermal lenses was adapted to an end-pumped laser configuration and led to very promising experimental results.

Recently we have successfully demonstrated the compensation of thermally induced lenses in transversally pumped laser rods by means of a self-adaptive compensating element (CE) placed inside the laser resonator. The CE comprised a thin liquid layer that absorbed a small fraction of the intracavity laser radiation to generate a power-dependent compensating lens [1]. This negative thermal lens that is generated in the CE adaptively compensated for the varying positive lens in the laser rod (such as a transversally pumped Nd:YAG rod). The advantage of liquids is that they generally have a very strong thermal dispersion, which makes that only a thin layer and low heating powers are required to generate the desired lenses. In order to generate a power-dependent thermal lens in the CE a radial heat removal is required. This was achieved by filling the compensating liquid in a gap between two glass rods placed in a cooling mount. With this the heat generated in the CE due to the absorption of the intra-cavity laser radiation is removed mainly in radial direction which induces the desired power-dependent temperature profile.

In the compensation scheme summarized above, the CE is arranged inside the resonator and the compensating lens has to be superimposed with the lens in the laser rod by means of relay optics. This set-up can be simplified by placing the compensating liquid layer directly at the location where it is needed. For transversally pumped lasers, the compensating layer is sandwiched in the middle between two laser rods [2]. With this the temperature distribution in the laser rod is transferred to the compensating medium directly by the close heat contact and no absorption of intracavity laser radiation is necessary.

This compensation scheme can also be adapted for end-pumped lasers. In this case, the compensating liquid layer is placed between the pumped face of the laser rod and a glass rod that serves as the HR end-mirror (see figure 1. a)). Again, the temperature distribution generated in the laser rod is transferred to the compensating layer by heat contact, leading to an optimum compensation of the thermally induced lens with varying laser power.

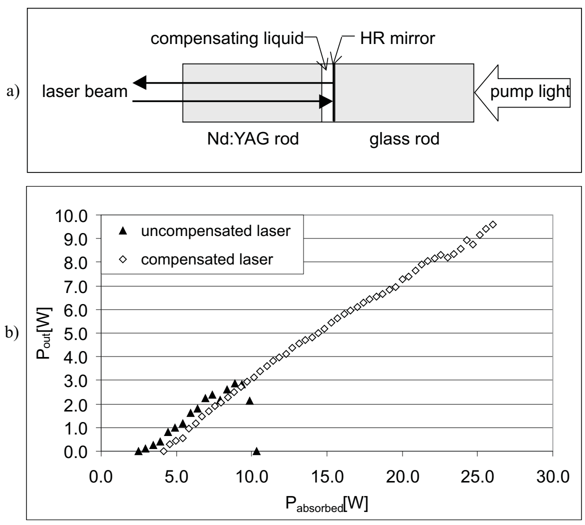

Figure 1. a) Compensation scheme; **b)** Output power

For the experiments, the laser rod was pumped with a collimated diode-laser beam which was focussed through the glass rod and the compensating medium onto the end-face of the laser rod. The two faces of the laser rod are AR coated (taking into account the refractive index of the compensating medium). The surface of the glass rod facing the compensating liquid is HR coated for the laser wavelength and AR for the pumping beam. For the compensation we used the optical coupling fluid OCF-446 (by Nye Optical Products, USA). The total

dioptric power of the thermal lens induced in the end-pumped and compensated laser was measured by means of a Mach-Zehnder interferometer. The reduction of the overall thermal lens leads to an increase of the pump power range over which the resonator supports stable TEM_{00} laser oscillation. Figure 1. b) shows the measured input-vs.-output curves of a compensated and an uncompensated laser. Without compensation the laser becomes unstable at an absorbed power of about 9.5W whereas the compensated laser stays stable up to the maximum available pump power.

[1] Th. Graf, E. Wyss, M. Roth, H.P. Weber; "Laser resonator with balanced thermal lens", Optics Communications **190** (2001), pp. 327-331

[2] Th. Graf, E. Wyss, M. Roth, H.P. Weber; "Adaptive thermal optics in high-power laser resonators", SPIE Proceedings "Laser Resonators and Beam Control V", **4629** (2002), (Photonics West 2002, San José, USA)

Appendix B

High-Power Nd:YAG Laser with Thermo-Optically Self-Compensating Amplifier

Conference Abstract

EPS-QEOD Europhoton Conference
"Solid-State and Fiber Coherent Light Sources"

Lausanne, Switzerland, 29 Aug. - 03 Sept. 2004

High-Power Nd:YAG Laser with Thermo-Optically Self-Compensating Amplifier

M. S. Roth, Th. Graf and H. P. Weber
University of Bern, Institute of Applied Physics, Sidlerstrasse 5, CH-3012 Bern, Switzerland
michelle.roth@iap.unibe.ch

Thermally induced optical distortions in the gain material are one of the most critical issues in high-power solid-state lasers since they limit the power range of the laser as well as the beam quality. Since thermal effects are power-dependent they need to be compensated for by adaptive methods. A very promising method is to exploit these very thermal effects themselves to generate self-adjusting lenses based on liquids or gels that can compensate for the thermal lenses in the laser material [1]. Several compensation schemes based on this method have already successfully been tested in experiments. Another scheme, the so-called thermo-optically self-compensating amplifier (TOSCA) has been analysed theoretically, e.g. in [2], but not been tested experimentally up to the present. One of the great advantages of the TOSCA is its very compact design. In this contribution first experimental results of the TOSCA concept are presented.

Fig. 1 shows a sketch of the experimental set-up. The compensating medium, a thin disk of a rubber-like gel is sandwiched between two laser rods mounted in a water-cooled glass tube. The laser is pumped by three stacks of diodes, each providing a maximum pump power of about 280W. As compensating media several materials such as silicones and polymers have been tested. The results presented below were attained with a polymer material originally made for fiber coatings. Thin disks with different thicknesses between 0.3mm and 0.5mm were prefabricated and mounted between the two laser rods whose faces were coated to match the refractive index of the compensating material.

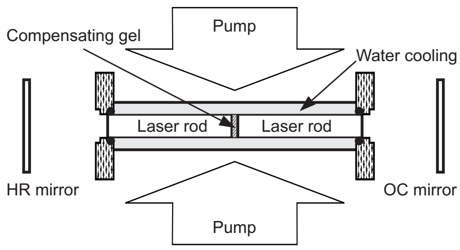

Figure 1. Set-up of the TOSCA

The results in Fig. 2 illustrate the reduction of the overall thermal lens in the self-compensated laser resonator. Compared to the uncompensated resonator the thermal lens is reduced by a factor 1.6 resp. 1.7 depending on the thickness of the compensating disk. This does not yet approach the results achieved with other compensation schemes but will be improved in future experiments. The reduction of the thermal lens leads to an improvement of the beam quality and an increase of the stability range of the laser resonator. Fig. 3 shows the output power of an uncompensated laser compared to the output curves of two compensated laser rods with different thickness of the compensating material. All measurements

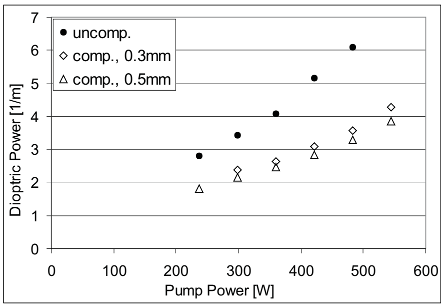

Figure 2. Dioptric power versus pump power

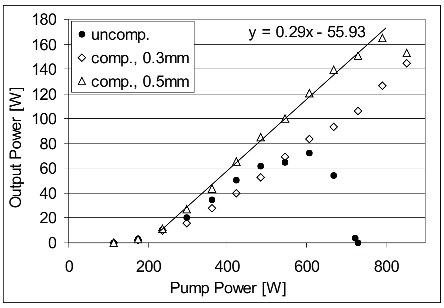

Figure 3. Output power versus pump power

were performed with a 40cm long resonator. Whereas the uncompensated laser reaches its stability limit at a pump power of about 600W the laser with a compensating disk of 0.3mm thickness supports stable oscillation up to 790W of pump power with an efficiency of 29%. With a 0.3mm thick layer of the compensating material the efficiency is reduced due to the absorbtion losses but on the other hand the laser is stable up to the maximum pump power.

[1] Th. Graf, E. Wyss, M.S. Roth, H.P. Weber; "Laser resonator with balanced thermal lens", Optics Communications **190** (2001), pp. 327-331

[2] E. Wyss, M.S. Roth, Th. Graf, H.P. Weber; "Thermooptical Compensation Methods for High-Power Lasers", IEEE Journal of Quantum Electronics **38** (2002), pp. 1620-1628

Varia

Publications

- Michelle S. Roth, Valerio Romano, T. Feurer and Thomas Graf, "Self-Compensating Amplifier Design for CW and Q-Switched High-Power Nd:YAG Lasers," submitted to Optics Express

- Michelle S. Roth, Eduard W. Wyss, Hansjuerg Glur and Heinz P. Weber, "Generation of radially polarized beams in a Nd:YAG laser with self-adaptive overcompensation of the thermal lens," Optics Letters **30 (13),** 1665–1667 (2005)

- Michelle S. Roth, Eduard W. Wyss, Valerio Romano and Thomas Graf, "Dual-Head High-Power Nd:YAG Laser with Thermo-Optically Self-Compensating Amplifiers," OSA *TOPS* **98,** Advanced Solid State Photonics 2005

- Michelle S. Roth, Eduard W. Wyss, Thomas Graf and Heinz P. Weber, "End-Pumped Nd:YAG Laser with Self-Adaptive Compensation of the Thermal Lens," IEEE Journal of Quantum Electronics **40 (12),** 1700–1703 (2004)

- Edy Wyss, Michelle Roth, Thomas Graf and Heinz P. Weber, "Thermo-Optical Compensation Methods for High-Power Lasers," IEEE Journal of Quantum Electronics **38 (12),** 1620–1628 (2002)

- Michelle S. Roth, Thomas Graf and Heinz P. Weber, "Self-adaptive compensation of thermal lenses in an end-pumped Nd:YAG laser," Proceedings of SPIE **5147 (1),** ALT'02 International Conference on Advanced Laser Technologies, 236–242

- Eduard Wyss, Michelle S. Roth, Thomas Graf and Heinz P. Weber, "Thermo-optical self-compensated amplifiers for high-power laser resonators," Proceedings of SPIE **5147 (1),** ALT'02 International Conference on Advanced Laser Technologies, 21–32

- Edy Wyss, Michelle Roth, Thomas Graf and Heinz P. Weber, "Self-adaptive compensation for thermal lenses in high-power laser resonators (2)," Proceedings of the 3rd International Conference on Adaptive Optics for Industry and Medicine 2002, 55–62

- Thomas Graf, Eduard Wyss, Michelle Roth and Heinz P. Weber, "Compensation of Thermal Lenses in High-Power Solid-State Lasers (1)," Proceedings of IQEC-LAT 2002

- Thomas Graf, Eduard Wyss, Michelle Roth and Heinz P. Weber, "Adaptive thermal optics in high-power laser resonators, Proceedings of SPIE **4629 (1),** Laser Resonators and Beam Control V 2002, 79–85

- Michelle S. Roth, “Adaptive Kompensation thermisch induzierter Linsen in Hochleistungs-Festkörperlasern”, Master Thesis, Philosophisch-Naturwissenschaftliche Fakultät, Universität Bern (2001)
- Michelle Roth, Thomas Graf and Heinz P. Weber, “Kompensation thermisch induzierter Linsen in einem endgepumpten Nd:YAG-Laser,” *Scientific Report,* Institut für angewandte Physik, Universität Bern (2001)
- Thomas Graf, Edy Wyss, Michelle Roth, Heinz P. Weber, “Laser resonator with balanced thermal lenses,” Optics Communications **190,** 327–331 (2001)
- Michelle Roth, Thomas Graf and Heinz P. Weber, “Kompensation thermisch induzierter Linsen mit Hilfe von Flüssigkeiten,” *Scientific Report,* Institut für angewandte Physik, Universität Bern (2001)

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Curriculum vitae

Name	Roth, Michelle Sylvie
Date of birth	13 October 1974
Place of origin	Fahrni BE

Education

2002 - now	PhD-student at the Laser Department, Institute of Applied Physics, University of Bern
1999 - 2002	Diploma-student at the Laser Department, Institute of Applied Physics, University of Bern; Thesis: "Adaptive Kompensation thermisch induzierter Linsen in Hochleistungs-Festkörperlasern"
1996 - 1999	Studies in physics, mathematics and ecology at the University of Bern
1993 - 1996	College: Feusi Gymnasium Bern

Experience

2002 - now	Lecturer at the Swiss College of Agriculture: teaching physics and mathematics
1996 - 2001	Part-time employment at the Swiss Federal Office of Private Insurance